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PARAMETERS GOVERNING URBAN VULNERABILITY TO FIRE FROM NUCLEAR BURSTS (PHASE I)

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SPECIAL SUMMARY

The Problem

The parameters affecting the fire vulnerability of U. S. Urban areas from nuclear bursts need to be identified, defined, and evaluated in terms of their relative importance, interactions, and sensitivity characteristics. The resulting information will be useful in fire-vulnerability assessment studies.

Findings

The parameters that govern urban vulnerability to fire from nuclear bursts have been identified and defined (Appendices A. Target Parameters, B. Weapon Burst Parameters, C. Atmospheric Transmission Parameters, D. Fundamental Processes of Ignition and Combustion, E. Fires From Causes Other Than Thermal Radiation, and F. Macro-Scale Fire Phenomena.) Sections 2 to 9 of the body of the report present the reliability of estimates and the ranking of parameters for each of the stages (in quasi-chronological order) of nuclear-burst-caused urban fire. Section 10 concludes with a comprehensive listing of parameters in decreasing order of importance and the ranking of these parameter groups for the following categories of urban fire response:

Type 1 -- Fire Vulnerability is Determined Primarily by the Extent of Fires Caused by Thermal Radiation. (Category A. Limited Thermal Shielding, Category B. Extensive Thermal Shielding.)

Type 2 -- Fire Vulnerability is Determined Primarily by Spread or Magnitude of Fire. (Category A. Spreading Fire of Conventional Magnitude, Category B. Conflagration, Category C. Firestorm.)

Type 3 -- Fire Vulnerability is Determined Primarily by Fires Resulting From Blast or Other Causes. (Category A. Blast-Caused Fires, Category B. Panic or False-Alarm-Caused Fires.)

Recommendation

Further research efforts should be made in sensitive areas where major information gaps exist such as the transmission of thermal radiation through clouded and hazy atmospheres, the detailed description of fuels (especially the fields of view or location of fuels), the mechanics of fire growth in enclosures, the mechanics of firespread (particularly firebrand propagation), and the fire behavior of large-scale convection columns and coalescence of fires. At the present time it is possible to assess incendiary vulnerability only via intuitive-stochastic approaches based on fire experience, and this approach is of doubtful reliability for civil defense purposes.

ABSTRACT

The parameters governing the fire vulnerability of U.S. urban areas from nuclear bursts have been identified, defined, and evaluated in terms of their relative importance, interactions, and sensitivity characteristics. The results will be useful in fire-vulnerability assessment studies.

A comprehensive listing of parameters in decreasing order of importance is presented with the ranking of these parameter groups for the following seven categories of urban fire response:

Type 1 -- Fire Vulnerability is Determined Primarily by the Extent and Number of Initial Fires Caused by Thermal Radiation. (Category A. Limited Thermal Shielding, Category B. Extensive Thermal Shielding).

Type 2 -- Fire Vulnerability is Determined Primarily by Spread or Ultimate Magnitude of Fire. (Category A. Spreading Fire of Conventional Magnitude, Category B. Conflagration, Category C. Firestorm.)

Type 3 -- Fire Vulnerability is Determined Primarily by Fires Resulting from Blast or Other Causes. (Category A. Blast-Caused Fires, Category B. Panic-or False-Alarm-Caused Fires.)

Recommendations are made for further research into significant areas where major information gaps exist.

SUMMARY PAGE

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SECTION 1

INTRODUCTION

1.1 STATEMENT OF THE TASK

The Office of Civil Defense sponsored this study at NRDL under work unit 2532A to provide necessary background information for future fire-damage assessment procedures and to provide guidance in the choice of research areas which can afford the maximum improvement in such procedures. The description of the study in the OCD Research Task Order was:

"Perform a comprehensive identification of the parameters pertinent to an assessment of the vulnerability to fire of urban areas from nuclear weapon attacks and other causes in the trans- and post-attack periods and an evaluation of their relative importance. The investigation should include, but not be restricted to, parameters associated with: level of ignition energy; atmospheric transmission; weather and climate; kindling fuel characteristics and distribution; fire development from thermal radiation-set ignition points and other causes such as blast and accidents; building geometry and arrangement; city plan and topography."

The term parameter is taken to mean physical and chemical variables, conditions and convenient groups of basic variables which can be used to describe a physical system and which when changed, cause a measurable change in the behavior of the system.

The study herein reported accomplished an identification and preliminary ranking by importance of all known parameters significantly affecting urban fire vulnerability.

1.2 OBJECTIVES OF STUDY

This study has been conducted to:

1. Identify and define the parameters that govern urban fire vulnerability.

2. Perform a sensitivity analysis of the various parameters for the purpose of determining:

a. The relative importance of each parameter to a full understanding of urban fire vulnerability.

b. The possible synergistic effects of interacting parameters.

c. What additional information is needed on the sensitive parameters and their interrelations.

3. Apply the results of the study to provide guidelines for anticipated fire vulnerability assessment studies and for further research requirements.

1.3 SCOPE AND APPROACH

This report is a comprehensive summary of the results of the interim study of urban fire vulnerability parameters. The reported study attempted to treat the problem of potential incendiary destruction of U.S. urban areas (as well as adjacent surroundings that might cause the urban area to become indirectly involved in fire), for the range of nuclear-attack conditions considered to be likely at the present time and within about a decade. The principal emphasis has been given to incendiary damage from thermal radiation, with blast and ionizing radiation being treated only insofar as they relate to the fire-vulnerability problem. Considerations of various fire-defense countermeasures have been excluded. Future studies will consider the full implications of countermeasures.

The problem of analyzing urban fire vulnerability is one of almost overwhelming proportions. This observation is perhaps obvious to anyone who has considered the problem in any depth, but we feel compelled to emphasize the point and to briefly elaborate on it. In the first place there is a great deal about fire and its behavior, particularly under the conditions of and on a scale appropriate to urban incineration, that is poorly understood or not understood at all. This deficiency can probably be corrected through research, of course, but there is a fundamental, intrinsically unresolvable, practical limitation to vulnerability analyses that is due to our inability to predict attack conditions and to describe target features in sufficiently microscopic detail. Clearly, we cannot hope to know, or be able to treat, on a national scale all of the information to which a detailed analysis of urban fire vulnerability may be sensitive. In fact, it would be an impossible task to usefully determine, for example, the characteristics, locations, and fields of view of <u>all</u> fuel items even for one major city. Conceptually, at least, adequate data-acquisition, handling, and storage facilities could be provided to accomplish the job; but before the data could be used (even while they are being acquired), they would no longer be accurate in microscopic detail because they are in a continual state of change. Such change applies as well to weather factors. Some forecasting is possible, but generally only on a macroscopic scale.

We can think of vulnerability analyses as lying between two extreme approaches which we might label "purely stochastic"* and "completely detailed" (or "deterministic"). A "purely stochastic" approach is one that evaluates the probable behavior of a class of similar or related elements of the system being considered from inductive (or in some cases intuitive) inference based on past experience. To the extent that it considers the properties of the system, it treats only class averages. A "completely detailed" approach is one that proceeds through a step-by-step, cause-and-effect deduction of the behavior of the system under consideration by evaluating deterministically (mechanistically if possible) the behavior of its individual elements. From what has been said about the impossibility of predicting attack conditions and of describing all of the elements of a target in precise detail, it is clear that the "completely detailed" approach is infeasible in general.

The "purely stochastic" approach, on the other hand, is designed for analyzing systems that can only be described in statistical terms. Unfortunately, however, the amount of detail in the output of the analysis will be even less than in the input, and the reliability of stochastic approaches may be poor. Depending on the scale of application, the predictability of attack conditions, and the amount of detail that can be practically obtained in surveying an urban target, a suitable blending of stochastic and detailed approaches will be used in future assessment procedures. The more stochastic the approach we are forced to use, the less we will find out, reliably, about the time-wise sequence of events and the destruction of specific resources by fire. (See Figs. 1 and 2.)

Strictly speaking, the fire vulnerability of an urban area depends on a given set of parameters in a definite way, which is not determined by the method of analysis used in attempting to assess it. Nevertheless, what we are really concerned with here is the dependence of our estimates of urban fire vulnerability on the parameters that appear to affect the results of feasible techniques of estimation, and different kinds of analysis can have very different sets of parameters. As an example, consider an analysis of fire spread, based on past fire experience, that might treat such parameters as fuel loading, building density, and average burning times of buildings as compared to an analysis, based on transport processes, that would involve parameters such as flame temperatures and emissivities, buoyant forces in hot combustion products, and thermal diffusivities of fuels. To the extent feasible, this report has been prepared with a diversity of possible analytical approaches in mind.

For the most part, we have found it impossible to perform a classical, purely objective sensitivity analysis of the dependence of urban fire vulnerability on the parameters involved. With the exception of a

* Webster defines stochastic as based on guesswork. We are using it in that sense to some extent, but mostly it here has the connotation of probabilistic.

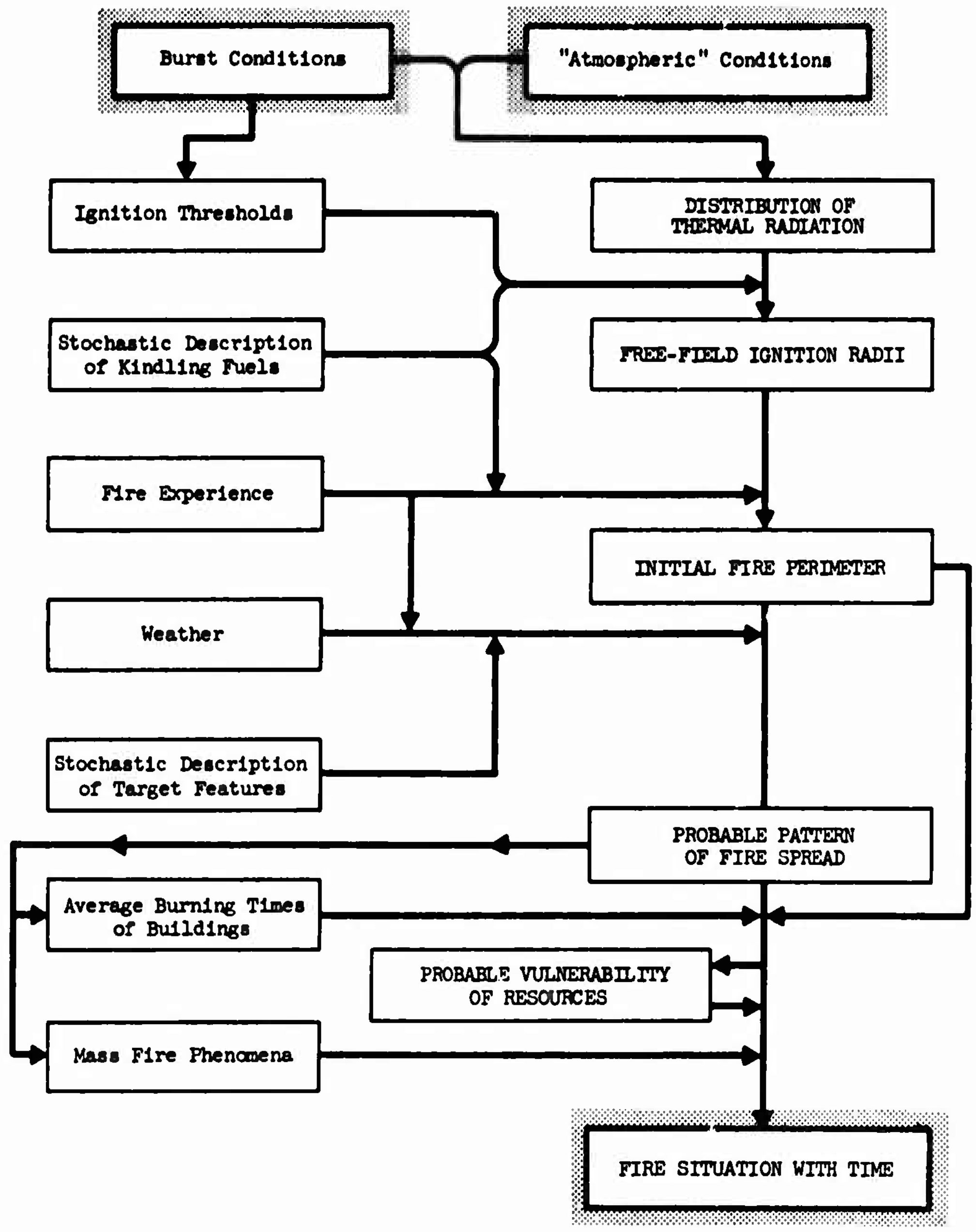


Fig. 1 Example of Stochastic Approach to Assessment Studies of Urban Fire Vulnerability

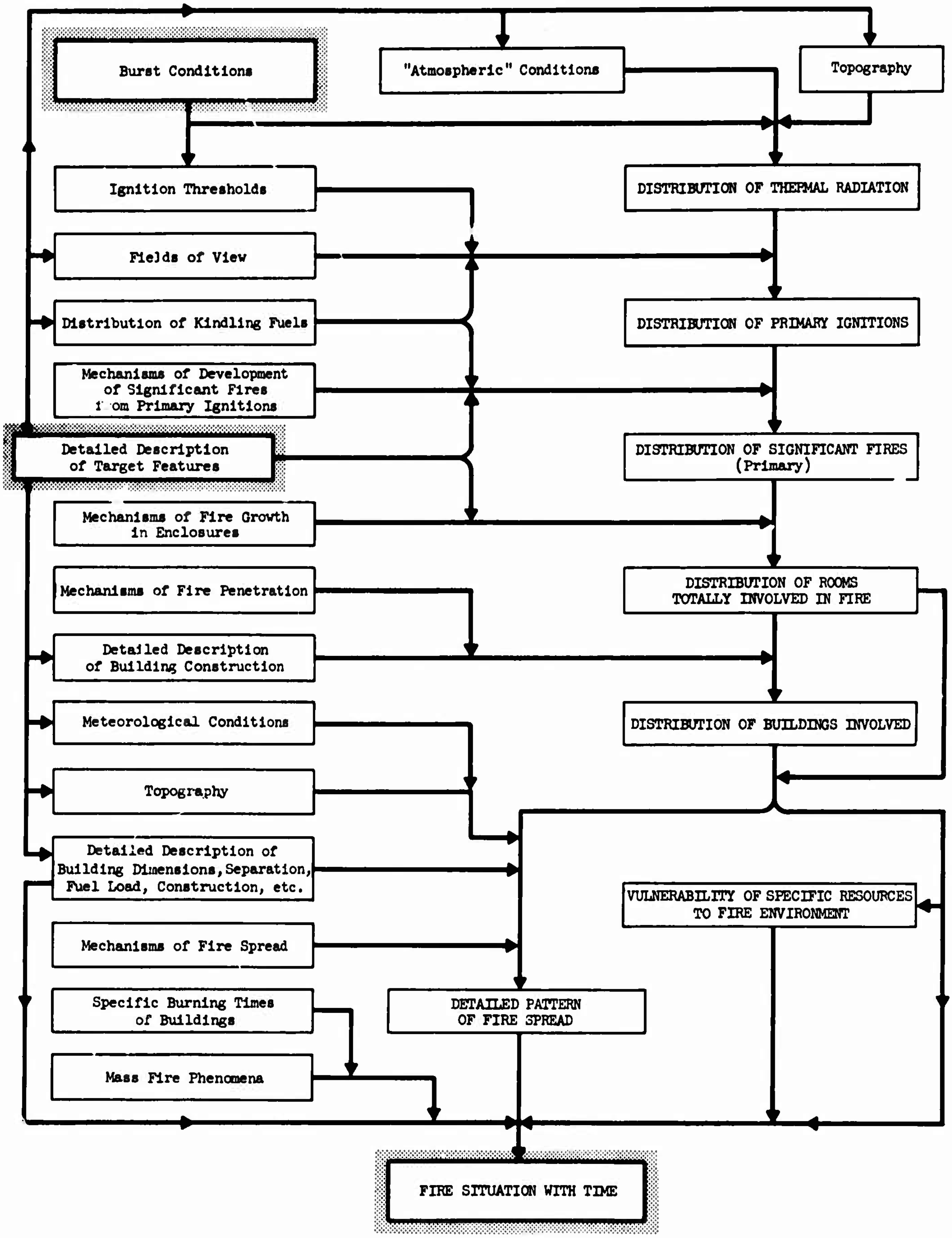


Fig. 2 Example of Detailed Approach to Assessment Studies of Urban Fire Vulnerability

few rare cases where empirical relationships exist, the importance of parameters has been derived primarily on the basis of judgment. This study considered the parameters involved in each stage of fire development in an essentially chronological sequence, beginning with an overall descriptive chronology of events (1.4), and then analyzing in detail each major behavioral phase--ignition, fire buildup, intraunit spread, interunit spread, large-scale interaction, and mass-fire development. Although this is a convenient (if not the only reasonable) framework on which to develop fire-vulnerability assessment procedures and is, therefore, a desirable framework within which to evaluate the basic parameters, it is not the most logical method of categorizing the pertinent subject matter for the purpose of discovering and enumerating the parameters. In an effort to (1) discover the parameters and their relationships to one another, (2) become fully apprised of the current, relevant technology and, as a consequence of these two reasons, (3) lend authoritativeness to the more subjective aspects of the sensitivity evaluations, we undertook an extensive search of the literature and consulted with a number of acknowledged experts in fields of weapons phenomenology, fire research, and fire experience. This information, along with some original information of our own, has been summarized in six state-of-the-art reviews of urban-target characteristics, weapon-burst conditions and characteristics, atmospheric transmission, ignition-combustion processes, causes of fires other than thermal radiation, and full-scale fire phenomena. These reviews, with citations of the sources, appear as appendices to the report and serve as the technical background material from which the parameters treated in the quasi-chronological, parametric analysis of the main part of the report are drawn.

1.4 SUMMARY REVIEW OF THERMAL-RADIATION EFFECTS AND FIRE CHRONOLOGY

By way of background to the subject of urban fire vulnerability, let us briefly review the overall picture of thermal-radiation effects and the anticipated sequence of events from fire initiation, through fire buildup and fire spread to maximum involvement (which may or may not be of the magnitude often termed a mass fire), to the point of burnout or fire termination. In addition, let us describe, define, and put into proper perspective some of the less universally accepted terms that are used in this report in discussing the available data and information more fully and precisely.

A nuclear-weapon explosion is accompanied by the release of a tremendous amount of energy in a very brief period of time. Much of this energy is radiated from the resulting fireball to its surroundings as a brilliant flash of light and near infrared thermal radiation. The amount of the thermal-radiation energy and the duration of the flash (or thermal-radiation pulse) is determined by the total energy yield of the weapon and the burst altitude above the ground. Except for surface

bursts (near-surface bursts to a lesser extent) and bursts at such great altitude that for all practical purposes they are above the atmosphere, the effective thermal radiation yield is a large, nearly constant fraction of the total yield. For the exceptions mentioned, the fraction is always somewhat smaller and under some conditions will range down to insignificant values.

For low-altitude bursts, the thermal-radiation pulse lasts anywhere from about a second or two for weapons of the nominal yield category to tens of seconds for weapons in the lower megaton-yield range, and may last as long as a minute or more for the very largest of weapons. Although both thermal and blast damage would be extremely heavy in an urban area immediately around ground zero, particularly for surface or near-surface bursts, the distances to which these effects would reach would be reduced to some extent by their interaction with the surface and its topographical features.

As burst altitude near the ground is increased (until clouds intervene*), the range of thermal effects increases rapidly because of the generally favorable change in the optical path (less shadowing by opaque objects such as buildings and hills, and less scattering by aerosol particles such as those of haze, dust, smoke, etc. Also a definite increase in the range of moderate to severe blast damage occurs, and blast damage in the ground-zero area tends to be less extreme.

With increasing burst altitude the duration of the thermal-radiation pulse becomes progressively shorter as long as the explosion occurs within the atmosphere, while the blast effects on the ground soon become light or nonexistent. The horizontal range (from ground zero) at which a given radiant exposure (time-integrated amount of thermal radiation incident on a unit area) is experienced decreases with burst altitude as the inverse-square loss of increased slant range overtakes the gains due to improved optical path. However, with respect to effects on the ground, this loss may be partially or completely offset by the shortened pulse duration.

From an incendiary viewpoint, the most important response of materials to the thermal radiation incident on them is ignition (glowing or flaming). Materials that are thermally thin** enough to be ignited by thermal radiation are termed primary kindling fuels. The act of igniting such materials in this manner is called primary ignition to distinguish it from other processes of ignition, such as blast-caused

* A significant decrease in thermal transmission results if the fireball is above a cloud layer.

** Here used in the sense of having a small value for the product of thickness, density, and heat capacity.

secondary ignition, and the ignition processes occurring during fire propagation. Accordingly, the fires resulting directly from primary ignition are called primary fires.

Immediately following the burst, even before the arrival of the blast wave, primary fires will extend out to distances at which the thermally thinnest of the kindling fuels in the target area receive their ignition threshold level of thermal radiation. At lesser distances, thermally thicker and thicker fuels will suffer ignition as they experience radiant exposures equal to or greater than their threshold levels. Close in to ground zero, even heavy construction materials may be involved in primary fire.

The distribution of primary fires will be governed by the distribution and kinds of kindling fuels throughout the target area, the degree to which they are shielded from direct, scattered, and reflected thermal radiation, the characteristics of the thermal pulse to which they are exposed, and the location of ground zero relative to the geographic coordinates of the urban area. Generally, threshold radiant exposures for the ignition of kindling fuels are less, the shorter and more intense the thermal pulse.

With the arrival of the blast wave, the picture may alter significantly. Large blast overpressures can reduce buildings and other target components to a chaotic jumble of broken and splintered pieces of both combustible and noncombustible materials. The blast wave may, under some circumstances, blow out primary fires; but it also has the capability of translating burning pieces into areas of blast-created kindling and of generally enhancing the susceptibility of the severely damaged area to fire spread.

If severe blast damage occurs in a heavily built-up area in which a large number of primary fires exist, a mass fire, in the form of either a conflagration or a fire storm, may be the ultimate result. Farther out from ground zero (or in any area suffering less severe blast damage as a result of a suitable combination of yield, altitude and/or peculiar topography), the blast wave plays a less dominant role in the fire picture. Although there may be considerable damage to buildings (which may in turn spawn secondary fires), the main contribution of the blast wave will be to generally lessen the fire resistance of the target by disrupting the integrity of buildings (caving in portions of roofs and walls, breaking windows, and unhinging doors), scattering combustible fuel elements into areas normally devoid of fuels, breaking water lines, blocking routes of access, and rendering ineffectual the usual means for combating fires.

In this area of the target, as well as in areas of primary fire with little or no blast damage, the subsequent history of the fire will follow a generally similar pattern. The kindling fuels involved in primary fires will range in size and fuel value from thin leaves and light wood-pulp products, such as newspaper, up to heavier items of furniture, kraft board cartons, drapes, awnings, and possibly even wall paneling and shingles. The sustained burning of the heavier items will typically constitute a significant fire (defined in Section 5.1), but the lesser items, depending on the proximity, orientation, and ignitability of adjacent fuels, can either burn out without generating a significant fire or ignite other fuel elements within a fuel complex of sufficient size to generate a significant fire. This phase between primary ignition and the development of a significant fire is termed fire start.

Once a significant fire has developed, the process accelerates through one of several sequences of events, depending on the nature of the environment (fuel distribution, subdivision, whether enclosed or not, etc.).

In the open, fire can propagate to other nearby fuel complexes. At this stage, the fire in the open spreads primarily through direct contact of flames or burning fuel elements with unignited fuels. It may spread in more than one direction. Its rate and direction of spread will depend on the concentration and distribution of nearby fuel elements and will be influenced by both wind and its own convective pattern. Lacking proximate fuel complexes to spread to, it consumes the available fuel and simply burns itself out. On the other hand, if conditions are favorable (low relative humidity and high fuel loading), the fire may "blow up" and spread at a rate many times greater than its rate of spread up to that point. At this stage, radiation-heat transfer and fire-induced winds become important factors in fire propagation.

Fires within structural enclosures generally follow a somewhat different path. Because of the nature of enclosures, high air temperatures and concentrations of unburned vapors often develop in the upper portion of the enclosure (as under the ceiling and above window and door openings). At some stage in this process, suddenly (almost explosively) the trapped gases "flash over," which creates an entirely new situation within the enclosure from which fire can spread rapidly either to connected enclosures within a set (intraunit spread) or to remote fuel complexes by ignition induced by radiation-heat transfer (interunit spread). This phase in the sequence of events is termed fire buildup.

Once the fire has built-up to a size as that described in the two preceding paragraphs, it can spread by one or more of several mechanisms involving conduction, radiation, and convection-heat transfer over relatively short distances and/or translation of burning solid fuels (called firebrands) over larger distances. Fires in external fuels do

not ordinarily constitute an extreme hazard to buildings except in situations where external fuel loading is high close to the buildings (as, for example, in certain suburban communities or storage areas) and, more especially, where there are routes of low fire resistance through which the fire may gain access, such as highly combustible exteriors (shingle or shake roofs, large wooden overhangs, open doorways or large windows without glass, deteriorated wood sidings, etc.).

Interior fires are likely to be of far greater concern. Once a room has become fully involved in fire, the chances of the building escaping nearly total fire damage without professional fire fighting are typically quite small. Exceptions to this are expected for fire-resistive structures having a low level of interior fuel loading. The fully developed room fire can penetrate through the floor, ceiling, walls, and/or existing openings (doors, windows, etc.).

Fire spread from building to building depends on a number of factors including separation distance, building construction, topography, and local or ambient meteorology. In heavily built up areas, fire will have a higher probability of spreading during early stages than it will in less heavily built up areas. High wind speeds will generally increase the rate of spread.

The overall fire situation at any time will be determined by the initial number and distribution of fires and their spreading rates based on the burning times for single buildings. If the fire spreads slowly, the burned out area will be a large part of the total fire-affected area. This situation typically leads to a moving-front fire no more than a few buildings deep, the usual situation in large, peacetime urban fires. On the other hand, if the fire spreads rapidly (and particularly if the number of initially spreading fires in a given area is large), mass-fire phenomena are likely to occur in which the intensity of the fire and the spread rate are enhanced by the large, concerted convective activity and resulting fire-induced winds.

Fires of such magnitude are referred to as conflagrations and fire storms. A conflagration is a mass fire that spreads usually in the direction of the natural wind along a front and builds up momentum generating its own wind. A particularly good example of this was the devastating fire in Tokyo on March 9-10, 1945. A fire storm is a mass fire that does not spread to any great extent beyond the initial mass-fire area. It generates a massive vertical convection column and high-speed winds around its periphery, which are generally directed into the fire area. The best known example of a fire storm was the fire in Hamburg in July, 1943.

SECTION 2

PARAMETERS FOR DESCRIBING THERMAL-RAD[illegible]ION DISTRIBUTION OVER THE URBAN AREA

2.1 GENERAL

The first step in assessing the fire vulnerability of an urban area is to determine the parameters that describe the potential free-field spatial and angular distribution of thermal radiant energy over the area and its temporal and spectral features. Appendices B and C describe the characteristics of thermal radiation for a broad range of nuclear-burst and atmospheric conditions. Parameters that govern the radiant-exposure levels (cal per cm^2) on the ground for the free-field case (ideal clear atmosphere and no opaque obstructions) are the energy yield of the weapon and the distance (slant range) from the fireball to the ground location of interest. Burst altitude has an effect on radiant-exposure levels for given radial distances from ground zero (horizontal range) primarily in the way it determines the slant range, but there is also an effect of change in fireball geometry for surface and near-surface bursts and, for very high altitude bursts, a decreased fraction of thermal energy emitted in times short enough to ignite fuel materials.

2.2 SPATIAL AND ANGULAR DISTRIBUTION OF RADIANT ENERGY

2.2.1 Spatial Distribution

Appendix C presents the state-of-the-art of estimating the transmission of thermal radiation through a variety of atmospheres, including clouded and hazy atmospheres, to ground surfaces having different albedos (reflection properties). For clear or hazy, cloudless atmospheres and when the fireball is near the surface, the radiant-exposure level at the ground depends heavily on the attenuation (absorption and scattering) properties of the atmosphere near the ground and is estimated with adequate precision from the along-the-ground visibility. For large slant ranges (relative to the visibility range), the transmittance falls off so rapidly with distance that the horizontal ranges for given radiant-exposure levels do not increase substantially with increased weapon yield (see Fig. 3). Maximum exposure orientation has to be in line of sight of the fireball. Calculations of atmospheric transmission that require only information about along-the-ground visibilities are probably of adequate reliability for distances out to one visibility range but their utility is limited

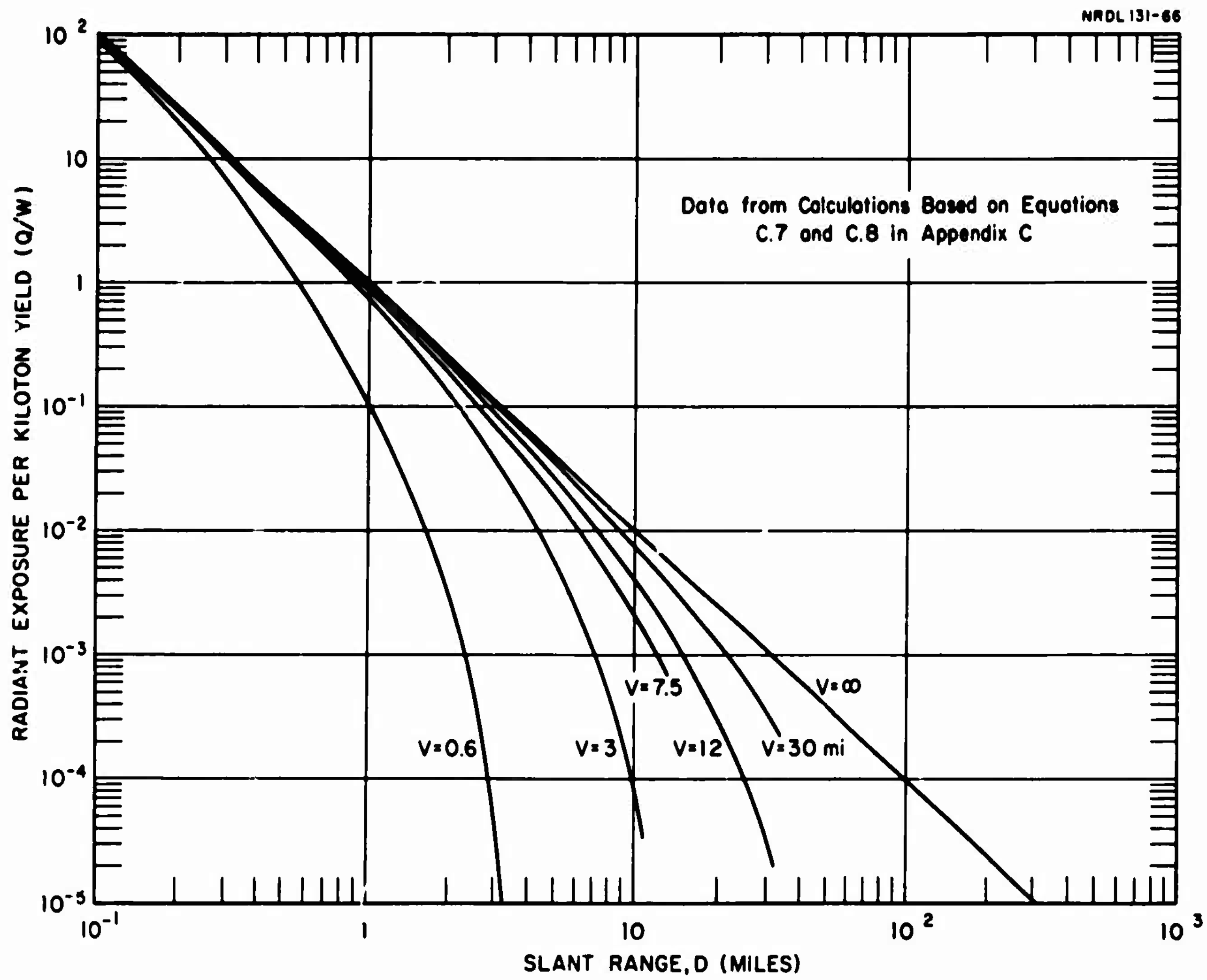


Fig. 3 Radiant-Exposure Vs Slant Range (D) for Several Visibilities

to surface or near-surface bursts of weapons having yields less than about 1 MT. The fireball for larger yield weapons is so large that even for surface bursts, a significant part of the thermal radiation received by a distant surface is propagated (at least partially) through air above the fairly uniform scattering layer on the surface through which visibilities are estimated. Thus, for most of the cases of interest to urban fire vulnerability problems (bursts larger than a megaton and for all yields when the burst point is more than about a quarter mile above the ground), visibility is not a completely adequate parameter in assessing free-field thermal distributions.

For the majority of cases of interest, it is necessary to resort to estimates of atmospheric transmission based on solar data. The governing factors in these cases are the transmission values of cloud and haze layers between the burst point and ground locations, the reflectances of cloud or haze layers above the burst point, and the albedo of the "ground" (or whatever surface exists between surface zero and surface points for which radiant-exposure levels are required). Equations for estimating atmospheric-transmission values for a variety of atmospheric conditions and for high and low surface albedos are presented in Appendix C. Figures 4 through 7 display radiant-exposure contours for assumed conditions and show the strong dependence of the free-field, thermal radiation distribution on cloud and/or haze transmission levels.

If the transmission equations are taken as reliable, then, for <u>uniform</u> cloud and/or haze coverage, the free-field distribution of thermal radiation over the target area can be described in a satisfactory deterministic way; but for the commoner case of broken clouds or uneven overcast, the distribution can only be described stochastically. Knowing enough details of cloud and/or haze structure for any given instant in time, a deterministic distribution can in principle be obtained, but the transient nature of the cloud and/or haze structure renders such an undertaking quite impractical.

For most situations, then, if we can expect to have only a probabilistic knowledge of the radiant-energy distribution over the urban area, is there any point in attempting to describe <u>in detail</u> the incendiary effects of the radiation? In our opinion, the answer is yes, for the following reasons: The propagation of radiant energy through a horizontally uniform atmosphere is normally a complex process, and is much more complex when broken clouds or other nonuniform scattering layers exist as they so commonly do. It is not possible at present to evaluate analytically the amount of distortion in the radiant-energy distribution over the surface caused by nonuniform scattering layers, but because of "random-walk" propagation, multiple reflections, and multiple scattering, it is reasonable to expect it will not be large in most cases. Thus, we are of the opinion that, except for infrequent situations of major discontinuities in the cloud deck (for example, a

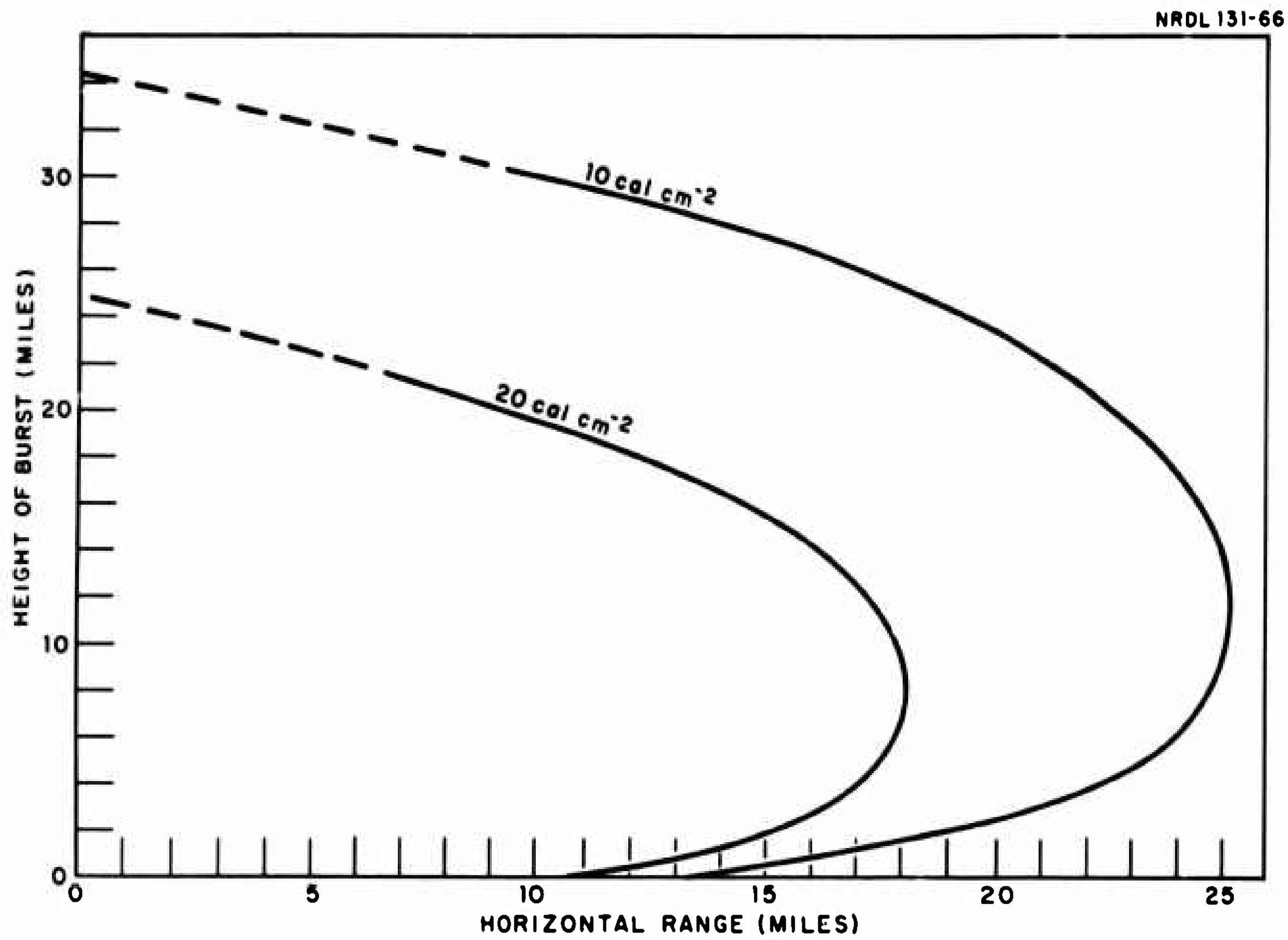


Fig. 4 10 and 20 cal cm^{-2} Radiant Exposure Contours for 10 MT Yield Nuclear Burst, Clear Standard Atmosphere (No clouds, 12 mile visibility, low surface albedo)

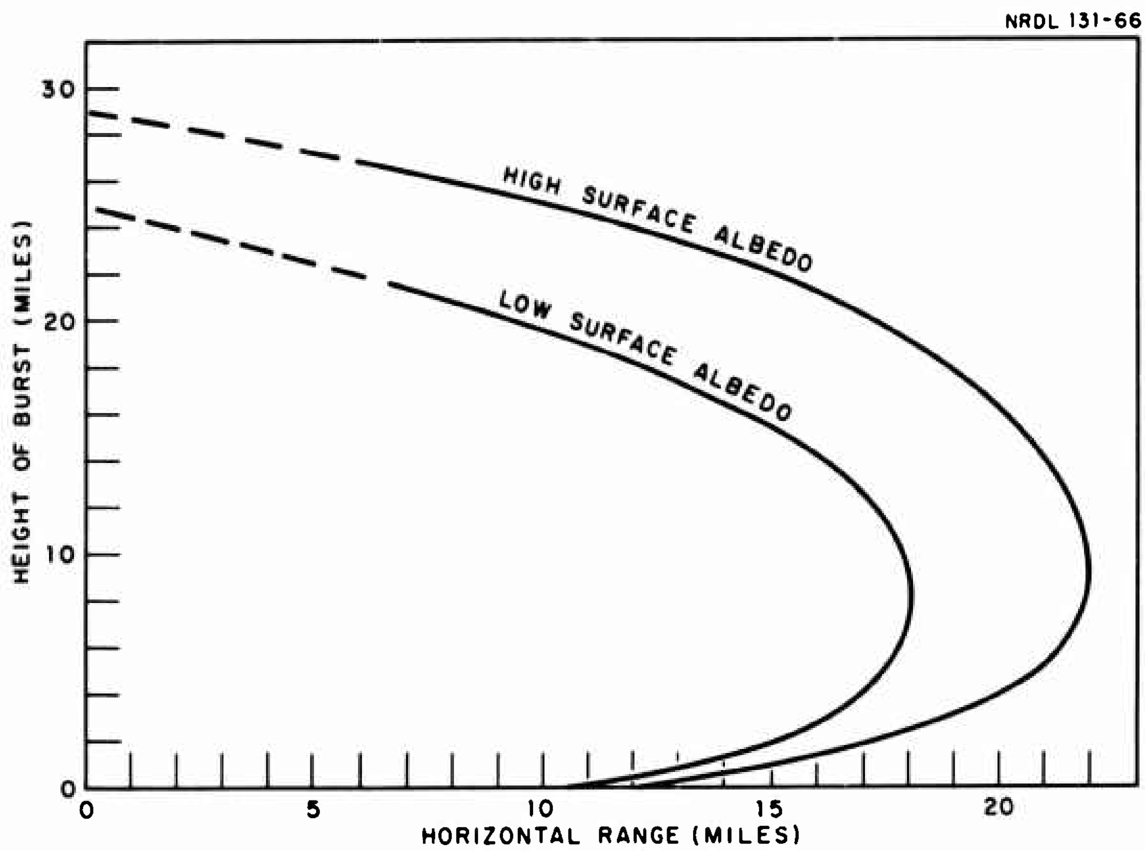


Fig. 5 20 cal cm^{-2} Radiant Exposure Contours for 10 MT Yield Nuclear Burst (Surface at sea level, 12 mile visibility, no cloud cover)

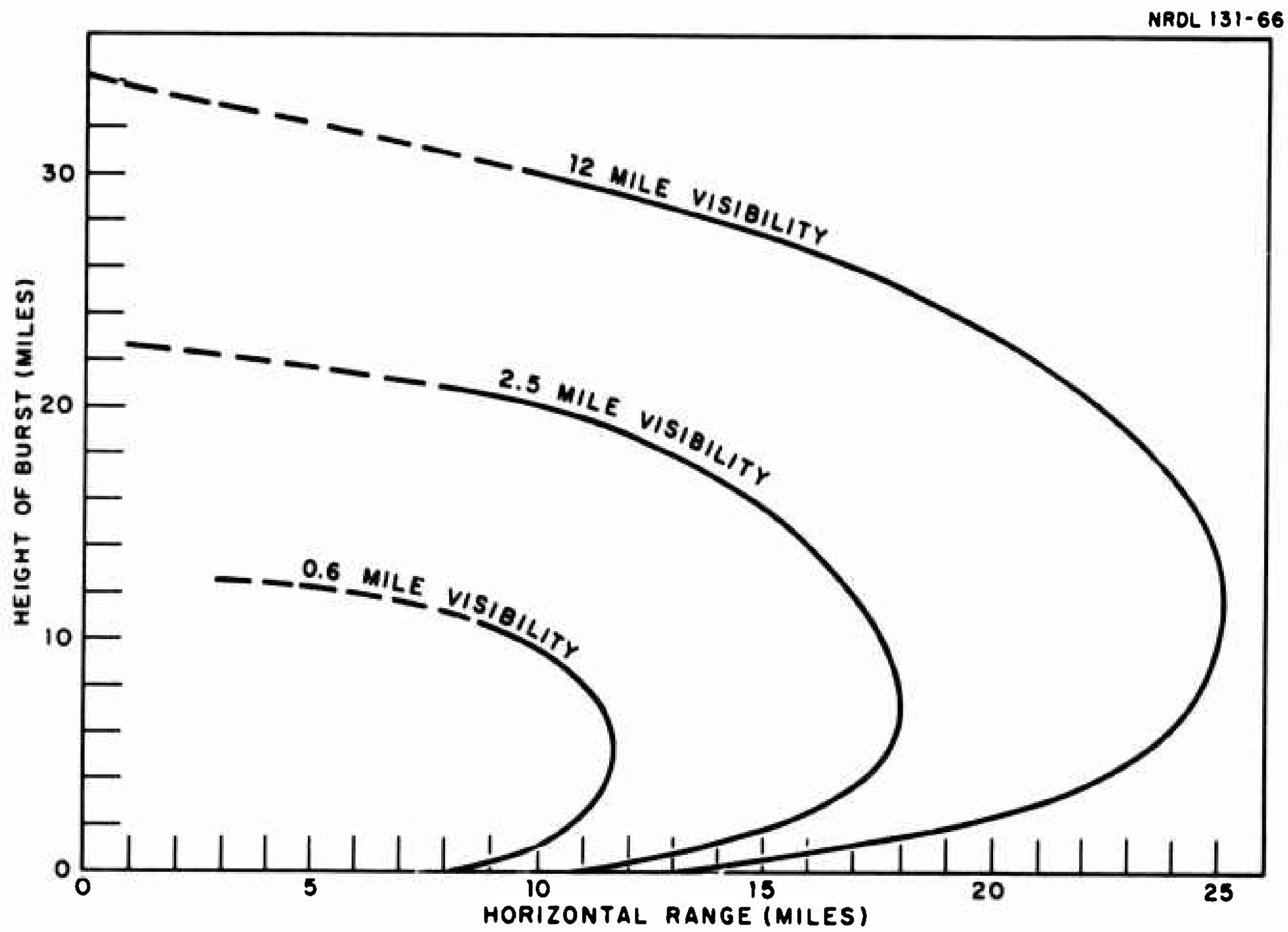


Fig. 6 10 cal cm^{-2} Radiant Exposure Contours for 10 MT Yield Nuclear Burst (No clouds, low surface albedo, surface at sea level)

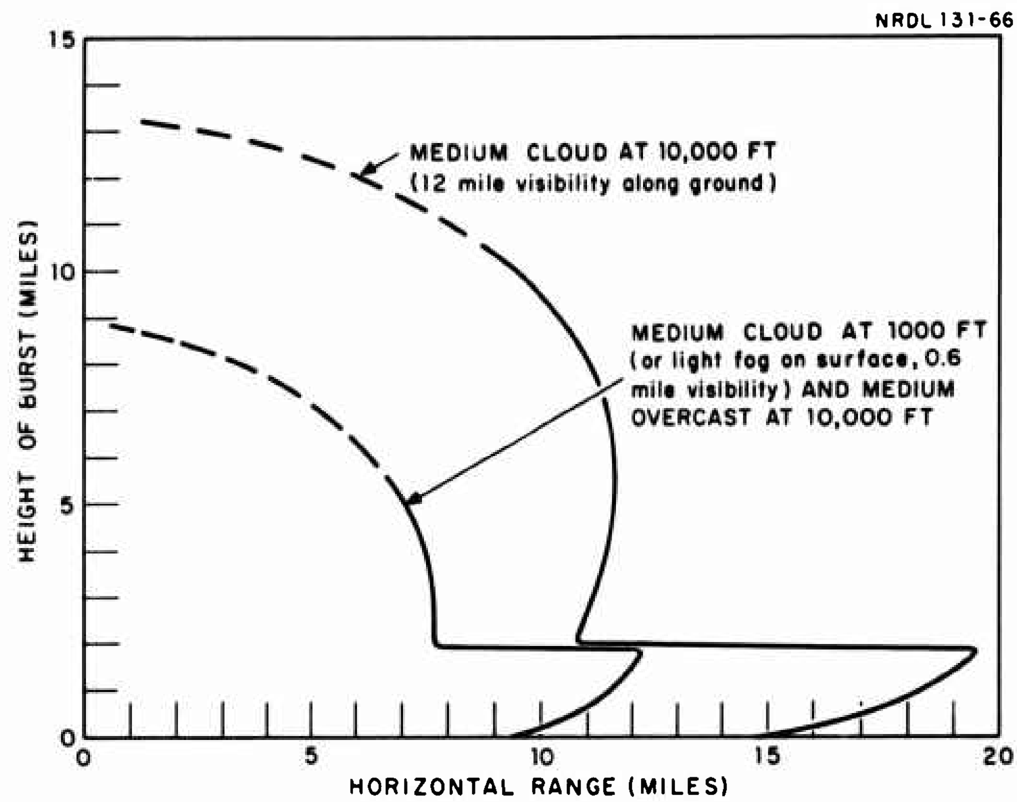


Fig. 7 10 cal cm^{-2} Radiant Exposure Contours for 10 MT Yield Nuclear Burst (Surface at sea level, low surface albedo.)

thunderhead front or a clear-sky rift in the overcast), the distribution of radiant energy over the target surface can be well-approximated using "spatially-averaged" cloud and/or haze conditions.

2.2.2 Angular Distribution

Somewhat the same situation applies to the angular distribution of radiant energy. It is apparent that it depends strongly on altitude of burst, scattering properties of the atmosphere, and reflecting properties of bounding surfaces. For a clear, cloudless atmosphere, the optimally oriented surface for exposure is one that is normal to the fireball line of sight, and the radiant exposure of a surface will decrease, to a good approximation, as the cosine of the angle between the normal to the surface and the line of sight decreases. Whereas for a hazy or clouded atmosphere, some situations of high surface albedo, and any situation where the visual range along the fireball line of sight is less than or about the slant range, optimal orientation will not necessarily be in the direction of the fireball line of sight, and the radiant exposure of a surface will not decrease as rapidly as the cosine of the angle between the normal to the surface and the optimal line-of-sight.

2.2.3 Reliability of Estimates and Ranking of Parameters

Estimates of radiant-energy distributions, both spatial and angular, are of satisfactory reliability only for weapons of tested yields detonated at altitudes less than about 30 miles with clear unclouded atmospheric conditions (or more precisely, for distances that are not large compared to the visual range along the slant path). Therefore, for a large proportion of the cases of interest, estimates of less-than-satisfactory reliability only are currently available for radiant-exposure levels over the surface of potential target areas, but it should be clear that satisfactory estimates are a prerequisite to estimating urban fire vulnerability.

The order of importance of the parameters involved is somewhat as follows: weapon yield, burst altitude, transmission of cloud and/or haze layers, cloud albedos, surface albedos, and visibility. Clearly, this order is not "sacred." Atmospheric variables can either dominate or become relatively unimportant, depending on the particular set of conditions.

2.3 TEMPORAL CHARACTERISTICS OF THE THERMAL PULSE

2.3.1 Dependence on Weapon-Burst Parameters

The effect of weapon yield, burst altitude, weapon environment, and other factors on the time-intensity pulse of thermal radiation is discussed in detail in Appendix B. The dominant effect of burst altitude is based

on air density. The thermal pulse (radiant power changing with time) for air bursts of all yields at altitudes to 20 or 30 miles (and possibly higher) can be satisfactorily represented by a single normalized function. The pulse duration can be described in terms of a characteristic time, which is usually taken to be the time to the second thermal radiant-power maximum, t_{max} (in seconds). This characteristic time is a relatively simple function of yield and the air density at the burst altitude, namely (to a satisfactory approximation),

$$t_{max} = 0.044\sqrt{W \rho_a/\rho_o} \quad . \text{(Eq. B.5, App. B)} \qquad (1)$$

W is yield in KT, ρ_a is air density at the burst altitude, and ρ_o is the air density at sea level. At higher altitudes, the pulse changes shape as a greater proportion of the thermal energy appears before the thermal minimum. The second maximum becomes smaller, and at altitudes of about 50 miles it disappears entirely. For burst altitudes below 50 miles, the equation above can be used to provide a rough estimate of t_{max}; as the second thermal maximum disappears, however, the characteristic time becomes ill-defined, but eventually can be taken to be the effective duration of the pulse, now roughly equal to t_{max} as given by Eq. 1.

No entirely satisfactory methods are available for interpolating between and extrapolating beyond the sparse experimental data for bursts above 50 miles. The pulse has two components; an intense initial spike composing 10% to 20% of the energy yield and lasting a few milliseconds, and a long tail composing 20% to 50% of the yield, which may last 0.1 to 100 seconds, depending on yield, burst altitude, and possibly weapon design (including vehicle components).

2.3.2 Dependence on Sudden Changes in Atmospheric Transmission

Another factor that could affect the temporal characteristics of the thermal pulse is rapid changes in the radiation-propagation characteristics of the atmosphere. Aside from twinkle and changes caused by the weapon effects, changes are not expected to occur rapidly enough to significantly alter the thermal pulse. Because of the extended size of the fireball, twinkle is probably not of an real concern. Weapon-burst-induced changes in transmission properties of the atmosphere (such as cloud dissipation, and dust and smoke generation) may in some circumstances play a role. These factors are discussed in more detail in Appendix C.

2.3.3 Reliability of Estimates and Ranking of Parameters

The temporal characteristics of the thermal pulse can be estimated with adequate reliability for effects purposes for the range of yields that have been tested (and probably to at least 100 MT) and for all but the highest altitudes of potential concern (up to about 50 miles).

Weapon yield and burst altitude are the dominant parameters and are of about equal importance. Parameters of much less (or practically no) importance are weapon design and rapid changes in atmospheric transmission.

2.4 SPECTRAL CHARACTERISTICS OF THE THERMAL PULSE

2.4.1 Dependence on Yield and Burst Altitude

The time dependence of the spectral characteristics of the thermal pulse on the weapon-burst parameters is considered in Appendix B. It is shown there that the spectral distribution is fairly well approximated by a black body whose temperature falls with time from an initially high value, which depends to some extent on the weapon yield, to a low value, which is effectively limited by the decreasing emissivity of the fireball and the 3μ wavelength atmospheric cutoff. The time average spectral distribution is not greatly different from solar radiation on the earth's surface. Large-yield weapons radiate a substantial fraction of their energy at lower effective black-body temperatures than small-yield weapons do. Although there is considerably more ultraviolet and infrared radiation emitted by high-altitude detonations, atmospheric absorption at wavelengths shorter than 0.3μ and in the water-vapor and CO_2 bands plus the prolonged duration of much of the infrared emission serve to minimize the differences as far as effects on materials are concerned.

2.4.2 Dependence on Atmospheric Scattering

Appendix C treats the subject of changes in spectral distribution caused by atmospheric scattering. An interesting synergistic effect involves (1) the angular distribution of radiation and its dependence on the scattering properties of the atmosphere and the spectral distribution of the radiation along with (2) the change in spectral distribution of the scattered radiation and its dependence on angle. As mentioned previously, a significant portion of the radiation that has undergone multiple scattering (for instance, at large distances relative to the visibility range from a low-altitude fireball) will be distributed over fields of view that do not include the fireball. This scattered-in radiation will exhibit a small, but measurable, shift to shorter wavelengths, while the directly-viewed fireball will appear redder.

Appendix D contains a state-of-the-art review of ignition of materials by intense thermal radiation. It can be readily inferred from this material that the spectral distribution of incident radiation plays a part in fire initiation only insofar as it affects the way in which the radiation is converted to sensible heat as determined by the optical properties of the irradiated material. Such conversion would not necessarily be the case for very short wavelength radiation, but the presence of the atmosphere in all considerations of urban fire vulnerability definitely limits the short-wavelength end of the spectrum.

2.4.3 Reliability of Estimates and Ranking of Parameters

The relative constancy of the spectral distribution of thermal radiation received at a distance (over atmospheric paths of practical concern) from nuclear fireballs plus the experimentally demonstrated insensitivity of ignition responses of typical kindling fuels to changes in spectral distribution (within the atmospheric window of approximately 0.3 to 3 μ wavelength) indicates that current estimates of the spectral characteristics of thermal radiation from nuclear bursts are of adequate reliability for incendiary assessment purposes. The order of importance of the parameters that determine the spectral distribution appear to be as follows: burst altitude, atmospheric absorption and scattering properties, and weapon yield. Though not considered here, weapon design may also have an effect.

SECTION 3

PARAMETERS DETERMINING DISTRIBUTION OF PRIMARY IGNITIONS FOR FREE-FIELD AND ACTUAL CONDITIONS

3.1 IGNITION RADII FOR FREE-FIELD CONDITIONS

In this section, we consider the idealized case of ignition of optimally oriented fuels exposed to the free-field distribution of thermal radiant energy, as developed in Section 2. The problem then is simply one of relating the ignition-threshold radiant exposures of fuels to (1) their physical properties, (2) their environment, and (3) the temporal and spectral characteristics of the thermal pulse to which they are exposed.

3.1.1 Dependence on Fuel Properties

The ignition behavior of cellulosic kindling fuels and its dependence on the physical properties of the fuels is considered in greater detail in Appendix D. The basic parameters are volumetric heat capacity (determined from thickness and density, or thickness and weight per unit area; specific heat capacity of cellulosic fuels is nearly constant), thermal diffusivity (estimated from density, or thickness and weight per unit area and from a knowledge of whether the fuel is natural or manufactured), optical absorptivity (this of course depends on the spectral distribution of the incident radiation), moisture content (which in turn depends on humidity and, for exterior fuels, on recent precipitation), geometry (that is, crumpled, folded, subdivided, layered, randomly mixed, etc.), and on extraneous contents. For noncellulosic fuels we must add chemical composition to the list of parameters that (although only a little experimental work has been done on such fuels) is not otherwise expected to differ substantially from the list for cellulosic fuels.

3.1.2 Dependence on Ambient Conditions

Environmental conditions that might be expected to influence ignition behavior are air temperature, local air currents, and local relative humidity (also recent precipitation for exterior fuels). In fact, however, air temperature within the normal range does not exert any significant influence. Local air currents can either enhance ignition (to the extent of causing some smoldering or glowing fuels to flame) or retard it by increasing heat losses (for long, low-irradiance exposures

where losses govern), but these effects are generally small. Fuels wet from recent precipitation will typically resist ignition altogether, although thin fuels can be dried out and ignited by suitably prolonged exposure to radiant heating. The moisture content of cellulosic kindling fuels bears a definite relationship to the local relative humidity. If the relative humidity has remained unchanged for a period of time sufficient to allow the moisture content of fuels to come to equilibrium, the moisture content of a fuel can be estimated. (See Fig. D.1, App. D.)

3.1.3 Dependence on Thermal Pulse Characteristics

The dependence of ignition behavior of cellulosic kindling fuels on temporal characteristics of the thermal pulse is described in detail in Appendix D. It has already been mentioned (Sec. 2) that the response of materials is dependent on the spectral distribution of the incident radiation in a way that is determined by the absorptance of the material, and since this is not usually a strong function of wavelength in the 0.3 - to - 3 μ range, ignition behavior is only weakly influenced by changes in spectral distribution.

3.1.4 Effect of Repetitive Exposures by Multiple Bursts

A factor that has not received any amount of attention thus far is the effect of multiple bursts (repetitive exposures) on the response of materials. Clearly, if a fuel is exposed to a series of repetitive exposures, all of which are (1) of insufficient intensity to cause an irreversible change in the properties of the fuel, and (2) far enough apart in time to allow reversible changes to return to the initial state (for all practical purposes), nothing will happen by way of damage to the fuel. But if any one of the exposures fails to satisfy condition (1) or if two or more exposures in combination violate condition (2), then there is a distinct probability that the fuel will be ignited by the series of exposures. It would appear at first sight that, if any one of the series of exposures is capable of igniting the fuel, the probability becomes unity. This is obviously so if the igniting exposure is the first of the series. But if preceding exposures have failed to ignite the fuel while depleting its volatile pyrolysis-product reserve, it might fail to ignite when exposed to a pulse that would surely have ignited it in its original state. However, this prospect seems quite unlikely and certainly not worthy of serious consideration in the usual situation of mixed fuels.

The cases of increased susceptibility due to reversible or irreversible changes in properties by a previous exposure does seem to demand serious consideration and is somewhat amenable to evaluation. The important reversible changes that occur in fuels as the result of exposure to subignition radiant levels are the generation of a temperature profile and the removal of moisture. The first of these is extremely

transient in nature, and it can be said categorically that if the repetitive exposures are more than a few seconds apart, they will not be able to build up the fuel temperature to a level that will cause ignition. Diffusion of moisture occurs more slowly than diffusion of heat, but the most that can happen to the fuel by the second reversible change is to get it "bone dry," in which state it is somewhat more easily ignited than when moist. But elevated temperatures are still a requirement, and unless the pulses are in rapid order, ignition cannot result.

However, when the exposures are in rapid order or when they are of flux levels such that individually they generate temperatures in the fuel surface that are several hundred degrees centigrade, then irreversible changes occur, such as pyrolysis of the organic constituents of the fuel. The resulting increase in the optical absorptance of the fuel (unless it was already black) plus the evolution of volatile fuel substances make the fuel susceptible to ignition by a subsequent pulse which by itself would otherwise have been incapable of igniting the fuel. Ignition by multiple bursts need only be considered, therefore, for rapid-order bursts where the radiant exposure from none exceeds the ignition threshold by itself and where together the time averaged irradiance will be at least 1 cal cm^{-2} sec^{-1} or more. If they are very close together in time, the sum of their individual contributions can be used to provide a single cumulative pulse for estimating ignition radii. If they are not nearly simultaneous, then it might be better to use a square-wave approximation.

3.1.5 Reliability of Estimates and Ranking of Parameters

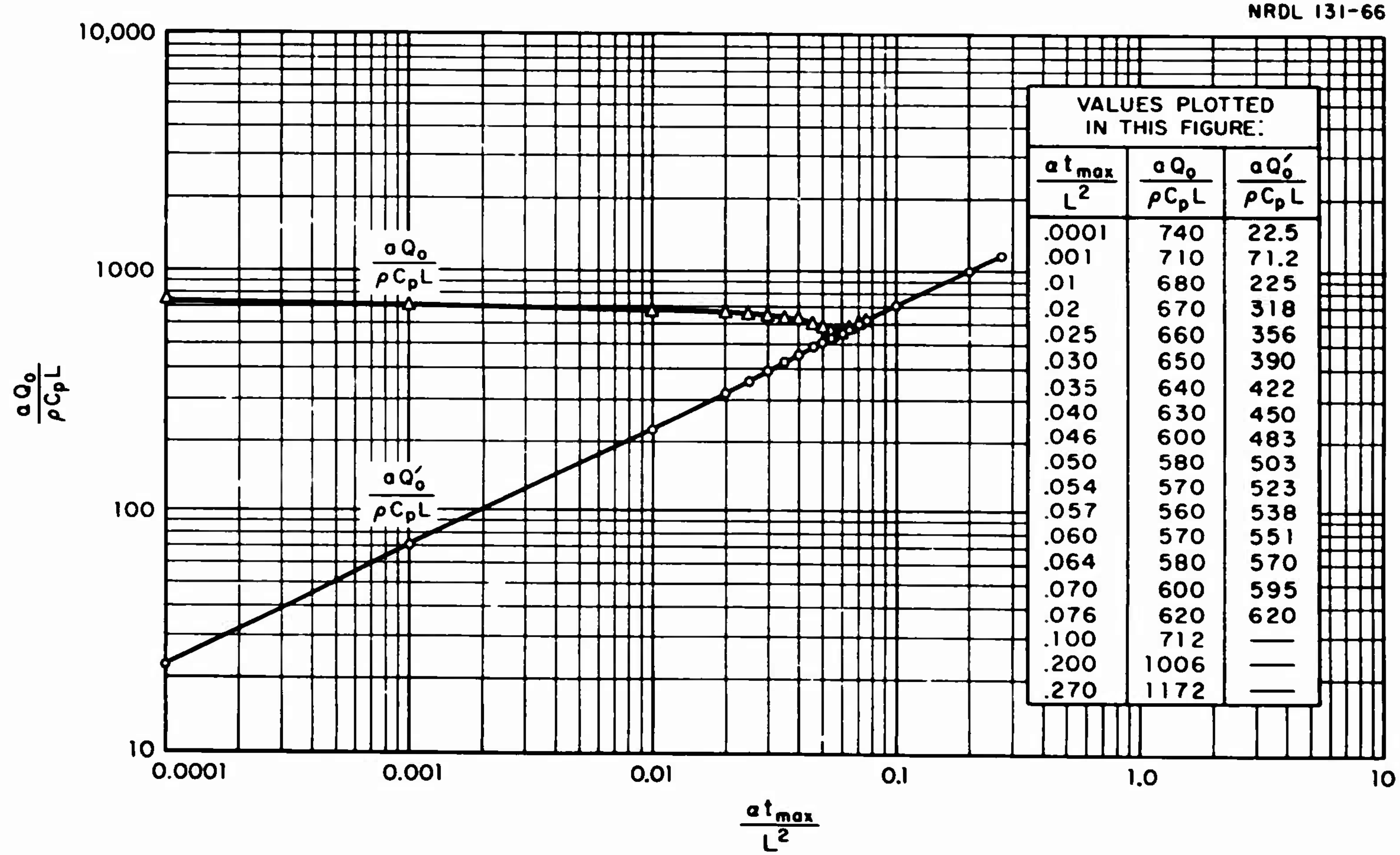
High-reliability estimates of ignition-threshold radiant exposure of cellulosic fuels of thickness L, density ρ, specific heat capacity C_p, optical absorptance a, and thermal diffusivity α can be obtained for the conventional nuclear-weapon thermal pulse of characteristic time t_{max} through the use of the following normalizing relationship:

$$\frac{aQ_o}{\rho C_p L} = f\left(\frac{\alpha t_{max}}{L^2}\right) \qquad (2)$$

for the range of $\alpha t_{max}/L^2$ as shown in Fig. 8; the functional relationship is:

$$\frac{aQ_o}{\rho C_p L} = 1500\left(\frac{\alpha t_{max}}{L^2}\right)^{0.2} + \frac{qt_{max}}{\rho C_p L} \qquad (3)$$

for larger values of $\alpha t_{max}/L^2$.



$\frac{a t_{max}}{L^2}$	$\frac{aQ_0}{\rho C_p L}$	$\frac{aQ'_0}{\rho C_p L}$
.0001	740	22.5
.001	710	71.2
.01	680	225
.02	670	318
.025	660	356
.030	650	390
.035	640	422
.040	630	450
.046	600	483
.050	580	503
.054	570	523
.057	560	538
.060	570	551
.064	580	570
.070	600	595
.076	620	620
.100	712	—
.200	1006	—
.270	1172	—

Fig. 8 Ignition Correlation Diagram for Cellulosic Fuels (Low Altitude Weapon Pulse)

Q_o is the threshold radiant exposure for moisture-free fuel; Q'_o is the value for transient (unsustained) cases. This value can be converted to the value for any desired relative humidity by multiplying by the appropriate factor determined from Fig. D.1, App. D.

The quantity q in Eq. (3) is an empirically determined quantity that depends primarily on the geometry of the fuel. It has values from about 0.8 for geometrically complex fuels to about 1.8 for plane-sheet configuration fuels (and could be somewhat higher in cases of considerable local air motion).

For relatively short exposures, uncertainties in the optical-absorptance values are the dominant contributors to uncertainty in estimating threshold exposures. At longer exposures, unreliability can result more from uncertainties in q values. Estimates of radiant exposure for ignition of a fuel whose properties are readily ascertained are probably good to better than 20% except for non-cellulosic fuels (or for cellulosic fuels which normally contain significant non-cellulosic constituents or have been treated, e.g., for fire retardancy) and for very long pulse durations for which errors of a factor of 2 or more are possible.

In approximate order of importance, the parameters that influence free-field ignition of materials are fuel thickness (more accurately the weight per unit area), optical absorptance, weapon yield, burst altitude, relative humidity (and, for exterior fuels, recent precipitation), local air currents, chemical composition, extraneous contents (such as water and carbon dioxide), fuel geometry (for long pulses only), source of fuel (whether natural or manufactured), spectral distribution of incident radiation, and for certain limited situations of multiple bursts the time between bursts. In some circumstances, ignition of exterior fuels would be dominated by ambient conditions-notably precipitation.

3.2 IGNITION RADII FOR ACTUAL CONDITIONS

3.2.1 General

Up to this point, it has not been necessary to consider the details of a particular urban target; but from here on, it will be necessary to do so to an extent dictated by the amount of detail required in the output from any attempted assessment of urban fire vulnerability, and hence, by the scale (that is, national, regional, or local) of the application. Obviously, if we require a completely detailed picture of the fire history in a particular U. S. city as it might occur following a specified nuclear-attack situation, we will have to be able to describe that city in great detail, perhaps on a house-to-house, room-by-room basis; but to attempt anything so detailed on a national basis is quite impractical. Recognizing the potential need for both detailed and

stochastic approaches, we will attempt to point out the differences in terms of information requirements, and scrutinize each set of parameters to discover the relative sensitivities of them to the different analyses.

In subsection 3.1, we considered ignition radii for free-field conditions -- the most idealized, nondetailed basis available for assessing the extent of primary ignitions. In this subsection, we consider ignition radii for actual conditions over an urban target -- by the detailed approach.

3.2.2 Dependence on Detailed Distribution of Kindling Fuels

Appendix A describes in some detail the features of an urban area that determine its fire vulnerability and some techniques that can be used to describe these features. The distribution of kindling fuels can best be determined by survey (preferably door-to-door, on foot). Such a survey is a large undertaking (even for a few dozen city blocks with a large team of qualified observers), and much of the information is of transient value (variable in validity, utility, etc.).

For many (or most) applications, it is infeasible to account for each and every item of kindling fuel in an urban area, its type, its location (relative to other fuels, whether exterior or interior, etc.), its ambient environment, and its field of view. It is highly desirable to seek generalizations to obviate the necessity of surveying every building, vacant lot, and neighboring suburban area in a city and for every urban area in the entire nation. Appendix A suggests example methods for breaking an urban area down into subareas (for example, by land-use classes). Typical or average features, including kindling-fuel parameters (abundance and location), can be determined and used for such subareas as the application warrants.

Regardless of the extent to which detailed surveys are attempted or average features are settled for, it is also highly desirable to establish certain constraints on requirements for urban input parameters. Constraints can best be established by specifying likely attack conditions. For example, if it is considered probable (in an assumed attack scenario) that a particular city will suffer one hit (or near miss) at a specific location relative to the urban complex, with a weapon of specified yield and burst altitude, then the input requirements are eased considerably. A certain area will likely suffer heavy damage from blast, and within this area (and perhaps within a significantly larger area that is more or less concentric with it) widespread fires are a certainty. Similarly, outside of a still larger concentric area, whose radius is readily calculated knowing the distribution of free-field radiant energy and the threshold radiant exposures for the ignition of the most susceptible fuels to be found around urban areas, primary fires will not occur.

Thus, we are presented with an annulus wherein the primary-fire outcome is not obvious and for which information about kindling fuels is required.

Within this annulus it is necessary to know, or to contrive an estimate of, the locations and abundances of kindling fuels, how they vary with time (time of day, day of week, seasons, etc.), and how they and their fields of view may be altered by the effects of a previous burst in the same area. More details are given in Appendix A.

3.2.3 Dependence on Fields of View of Kindling Fuels

The major difference between free-field and actual ignition ranges is attributable to the variable and typically limited fields of view of kindling fuels in actual urban targets. It is the exceptional kindling-fuel item that sees enough sky to receive directly all of the thermal radiation incident on the optimally oriented, free-field-exposed surface, other conditions being equal. Some kindling fuels may receive more by reflection enhancement, but such occurrences will probably be rare. Generally speaking, only those kindling fuels that view the sky, or the part of the sky in which the fireball appears, will be ignited at distances approaching the free-field limit. Furthermore, these are probably the only fuels that will be ignited at <u>any</u> distance* except where there is a relatively large component of the radiant energy scattered or reflected back at angles significantly displaced from the fireball line of sight. Examples of the exceptions would be found at relatively short distances from surface zero when the atmosphere is highly scattering and/or when a large portion of a kindling fuel's field of view is mainly filled with a highly reflecting surface. The first of these exceptions depends on (1) the subject of angular distribution of radiant energy, as discussed in 2.2.2, and (2) the fields of view of kindling fuels that see a large amount of sky but not the fireball. The second requires a knowledge of (a) the fields of view of kindling fuels that neither see the fireball nor a large amount of sky, and (b) the reflecting properties and exposure levels (free-field may not do) of the surfaces that occupy most of the field of view.

Detailed knowledge of kindling-fuel fields of view is at least as hard to acquire as detailed knowledge of their locations and abundances. The same practical limitations apply to surveys attempting to gather such information, and the same kinds of constraints should be applied whenever possible. Actually, however, the field of view can be utilized in many

* It must be remembered that kindling fuels are defined in terms of ignitability by thermal radiation, and therefore at high radiant exposure levels, heavier materials (for example, shingles) are kindling fuels.

instances to establish survey limitations. If, on brief inspection, it can be determined that the fields of view of a kindling-fuel complex (furniture in a room, packaging materials in a warehouse, etc.) prohibit ignition of any of the items in the complex for appropriate sets of attack conditions, then quite clearly there is no need to survey the contents of the complex (at least as far as primary ignition assessment is concerned). For example, in a suburban tract of homes located south of the main industrial center of a city (the assumed target), all rooms of southern exposure might be excluded from a proposed survey of kindling fuels. It should be remembered, too, that fields of view of interior kindling fuels change with time. Another complication is introduced if more than one burst is considered likely. If the burst point varies, the fields of view vary accordingly. All of these factors are discussed in more detail in Appendix A.

3.2.4 Reliability of Estimates and Ranking of Parameters

Obviously, the reliability of any detailed estimate of the actual distribution of primary ignitions in a particular urban target depends heavily on the level of information about the kindling fuels in the urban area. Complete knowledge of the type, location, orientation and field of view of every kindling-fuel item in a particular urban area would permit calculation of the primary-ignition distribution over that area to a level of reliability limited only by the reliability of estimates of the spatial and angular distribution of radiant energy for the free-field case suitably modified by local reflecting surfaces. Typically, however, it is not feasible to know all about every item of kindling fuel at any instant and accordingly more stochastic descriptions of fuel distributions and fields of view will have to serve. The extent to which the stochastic descriptions will limit the reliability of the resulting estimates will depend largely on the ingenuity employed in choosing the technique for obtaining the stochastic description. The more homogeneous the urban subareas are to which average values of fuel distributions and fields of view are assigned and the more the fuels are subdivided into classes of type, location, orientation, field of view, and environment, the more reliable will be the resulting estimate of distribution of primary ignitions.

In addition to the parameters that govern ignition radii for free-field conditions, as described in 3.1, the parameters that will determine the actual ignition distribution for a particular urban target, are, in the approximate order of sensitivity, (1) the slant range from kindling fuels by type relative to the burst point, (2) the fields of view of kindling fuels relative to the fireball line of sight, (3) whether the fuel is interior or exterior, (4) the angle of the fireball line of sight from points in the annulus of uncertain primary fire outcome relative to the horizontal (or vertical), (5) the heights of buildings relative to distances between them, (6) the locations of trees and other

shielding bodies relative to buildings and other concentrations of fuels, (7) the optical properties of obstructions which fill substantial parts of the fields of view of kindling fuels (primarily, their opacities and the reflectance characteristics of their surfaces), (8) the fuel orientation, and (9) the "homogeneity" of the sensitive parameters within urban subareas (if, as will commonly be necessary, the target is stochastically described).

SECTION 4

PARAMETERS DETERMINING THE RELATIVE IMPORTANCE OF PRIMARY FIRES AND FIRES FROM CAUSES OTHER THAN THERMAL RADIATION

4.1 GENERAL

In addition to primary fires ignited by thermal radiation, fires can be expected to result from other weapon effects (secondary fires), and even from human error and panic during and after the attack (tertiary fires). The most important cause of secondary fires is undoubtedly air-blast, which represents a much larger fraction of weapon energy than other secondary weapon phenomena (about half the yield of a low-altitude burst).

The relative importance of primary and secondary fires was a matter of some disagreement between the American and British surveys of the effects of nuclear explosions on Hiroshima and Nagasaki. Later studies have partially resolved these discrepant interpretations of the observations; the conclusions of these studies will be presented following a discussion of secondary-fire mechanisms. References to these studies and to the British and American surveys of Japan are cited at the end of Appendix E.

4.2 BLAST-CAUSED FIRES

For a fire to occur, three factors must be present: fuel, oxygen, and a source of heat or ignition energy. The thermal pulse from a nuclear explosion supplies the necessary ignition energy for primary fires, but the blast wave cannot ignite materials directly; instead, it must displace already existing energy sources and ignitable fuels so that they come into contact. The probability of such contacts occurring from random displacement is obviously low unless the available quantities of fuel and energy are large. The probability may also be increased if some of the fuels can subsequently flow or diffuse over a large area, that is, if they are in a liquid or gaseous state. Because of their convenience and economy, such fuels (natural gas, fuel oil, etc.) are widely used in the United States for heating, cooking, and other purposes, and thus may constitute important potential secondary-fire hazards. In the Japanese atomic bombings, the three most important sources were heating, cooking, and electrical systems, which together initiated nearly 90% of the secondary fires whose causes could be identified.

In most structures, gas and electrical lines and attachments for appliances are built into the walls; thus, damage to these utilities and the probability of resulting fire would be expected to be correlated with the degree of damage sustained by the structures themselves. A conservative estimate of the extent of blast-caused fires may then be taken as the range of moderate damage to exterior and interior walls of the structures of interest. For typical wood-frame construction homes, this range would correspond approximately to the 2-psi-peak overpressure contour.

4.3 FIRES FROM OTHER CAUSES

Other weapon phenomena besides thermal radiation and blast include (1) ground shock, (2) initial radiation (high-energy gamma and neutrons), (3) residual radiation (fission-products fallout and induced radioactivity), and (4) the electromagnetic pulse from the explosion. None of these effects is likely to be a significant cause of fire. Ground shock from a surface burst attenuates rapidly and is less important than air blast beyond 2 or 3 crater radii from the explosion, while ground shock induced by the blast wave from an air burst will be less damaging to above-ground structures than the air blast itself. Electromagnetic-pulse-induced surges in transmission lines may open circuit breakers, but are unlikely to cause much sparking or wiring overload.

Tertiary (human-caused) fires will in all likelihood be much less numerous than primary or secondary fires except at extreme ranges where the direct weapon effects are much attenuated. In any case, tertiary fires will almost certainly not contribute significantly to any mass-fire phenomena.

4.4 RELATIVE IMPORTANCE OF CAUSES

In a study of the Japanese nuclear explosions, conventional explosions, and earthquakes (see App. E) it was found that <u>secondary</u> fires occurred with a probability of about 0.01 per 1000 sq ft affected; for residential units of ~1000 sq ft area, this means that about one fire broke out in every 100 buildings destroyed. We have assumed previously that this probability will be fairly constant out to about the 2-psi-peak overpressure contour.

Other studies have indicated that, in this region, the probability approaches 1 that at least one <u>primary</u> fire would occur in every building exposed to the thermal pulse of a large weapon (at a range of 17 miles, which is the 2-psi overpressure radius for a 10-MT explosion at optimum burst altitude, the radiant exposure could be 20-30 cal/cm^2 on a clear day). Thus, if atmospheric transmission characteristics are favorable, primary fires from a megaton-range weapon should be at least two orders of magnitude more important than secondary fires out to a range of several

miles, and even more important at greater distances. On the other hand, if thick clouds, fog, or smoke intervene, the range and number of primary fires could be considerably reduced.

The fundamental constraint governing the relative importance of primary and secondary fires is the transmissivity of the atmosphere. This constraint and other relevant constraints (as determined by information cited in the appendices), in a rough order of importance, are included in the following list:

(1) Atmospheric transmissivity.

(2) Burst altitude (for high bursts, the effect of blast on the ground may be insignificant; whereas for bursts near the surface, target elements may be shielded from the thermal pulse by buildings, vegetation, terrain features, or dirt thrown up near ground zero).

(3) Weapon yield (for good visibility conditions, the ratio of radiant exposure to a given blast overpressure tends to increase with yield, at least up to a few megatons). Weapon yield is synergistically related with (1) Atmospheric Transmissivity.

(4) Target characteristics: relative concentrations of primary-fire hazards (trash, exposed curtains and upholstery, etc.) and secondary-fire hazards (gas lines, flammable liquids, etc.).

(5) Fuel-use patterns (affected by time of day, season, prevailing weather, etc.).

In an attack on a typical U.S. urban area with a weapon of a few megatons' yield, primary fires should be much more numerous than secondary fires, even with less-than-perfect atmospheric-transmission characteristics. Only under extreme atmospheric conditions, for example, a heavy overcast below the burst, could the extent and number of primary fires be reduced to such a degree that it might become necessary to consider the contribution of secondary fires.

SECTION 5

DISTRIBUTION OF SIGNIFICANT FIRES

5.1 DEFINITION OF SIGNIFICANT FIRE

Knowledge of the number and distribution of "points of primary ignition" is not enough information on which to base a description of the primary incendiary hazard of nuclear attack. Clearly, there are many kindling fuels (generally, the most susceptible ones) in a typical urban target that, after being ignited by the thermal pulse, cannot generate a destructive fire because they have insufficient fuel value to ignite proximate fuels or are sufficiently separated from them. As examples, consider dry grass between opposing lanes of traffic of a divided highway, papers on a metal desk or table, wind-blown litter against a building of masonry exterior, or even an upholstered chair in a fire-resistive office. If ignited, such kindling fuels are not apt to do anything more than burn themselves out. In contrast, a single ignited newspaper lying on an overstuffed couch in a typical American living room has at least a fair chance of initiating a fire that, if left alone, will destroy the building and possibly spread to adjacent buildings. Apparently, it is not enough to consider the size of the kindling fuel alone. Rather, we must include in our consideration the local environment of the ignited fuel if we are to get a realistic definition of significant fire -- the primary fire hazard.

One conceptual approach to a definition of significant fire involves comparing the heat release, in space and time, of the ignited fuel element or complex with the heat release of an incendiary bomb. This approach is convenient, since we have some knowledge of the efficiency of that kind of weapon gained from experience. Thus, for example, the burning newspaper alone does not represent a significant fire, but together with the couch, (assuming that the newspaper is capable of igniting the couch), sufficient fuel is arranged in such a way that an amount of energy is released in a spatially and temporally concentrated way so as to be equivalent to a conventional World War II incendiary bomb. Thus we could, as suggested originally by M. G. Gibbons (at the DASA/OCD Fire Phenomenology Workshop, 1-3 Feb. 1965), define a significant fire in terms of an "incendiary-equivalent" amount and arrangement of fuel which in turn might be defined, somewhat arbitrarily, as capable (on being ignited) of releasing 20,000 Btu from an area no greater than 1 sq yd in 10 min or less.

The fire assessment procedure, then, would amount to counting "incendiary equivalents" in each exposed locale and to comparing the number to the estimated number of incendiary bombs required to generate a destructive, self-propagating fire in that locale.

Although it is desirable to have an unambiguous definition of significant fire so that such fires might be differentiated from all other more transitory forms of incipient fires, the exact nature of the definition will vary somewhat from application to application. The definition given in the previous paragraph is a useful one, perhaps, for a semidetailed analysis of primary fires based on an extensive survey of fuel contents of buildings, but it requires too much target information to be usable in purely stochastic analyses and it is too restrictive for mechanistic analyses. In this report, we attempt to give consideration to the complete spectrum of analytical approaches. For this reason, we choose not to define a significant fire in any such arbitrary and restrictive terms as contained in the foregoing "incendiary equivalent" concept. We might simply describe a significant fire as a fire of such intensity and magnitude that it provides a source from which fire will propagate with high likelihood, bearing in mind,that, from a practical view, the propagation referred to is on a scale corresponding to room or building dimensions. Such a description is clearly unsatisfactory as a precise definition of the significant fire. It provides nothing more than a gross "feeling" for the difference between the fire which has the potential of becoming a serious problem and the one which is obviously of transient character. Neither does it restrict our flexibility of approach. The definition then should be made to fit the particular application, and at appropriate places in this report, where specific applications are discussed (see for example 5.2.1, 5.2.2 and 7.1.4), additional characterization of the significant-fire concept will appear.

5.2 RADIAL PROBABILITIES OF SIGNIFICANT FIRES BY NONDETAILED, STOCHASTIC ESTIMATE

5.2.1 Estimates Based on Free-Field Ignition Radii

Radial probabilities of significant primary fires can be stochastically estimated by using free-field ignition radii for abundant fuels in urban subareas and by assuming certain relationships between primary ignitions of those fuels and initiation of significant fires based on fire experience and limited experimental results. By way of illustration, let us consider a typical example of the kind of stochastic approach that currently can be used to give answers.*

* Based on private communication from R.M. Rodden, Stanford Research Institute.

The abundance of the more common, readily ignited kindling fuels in various use-class subareas of urban targets of a few selected cities have been surveyed and estimated (see App. A). Although the estimates need updating and improving, they provide some indication of which fuels might be expected to play major roles in early fire development in each subarea. For residential areas, the more frequently observed fuels of kindling weight* ranged in ignition susceptibility from dry newspaper to heavy fabrics (drapes, furniture coverings, etc.), with newspaper by far the most common. Fire experience and limited experimental evidence suggest that ignited newspapers in residential rooms ordinarily present a minor fire hazard, whereas ignited drapes, bedspreads, and upholstered furnishings constitute a high level of hazard. (See discussion of requirements for flashover in App. F.) On this basis, it seems quite reasonable to assign a low probability P_1, say 1% or 10%, to significant fires (in residential buildings) at distances corresponding to free-field radiant exposures that can ignite newspaper, and a high probability P_2, 50% or 90 (or even 99)%, of significant fires at distances corresponding to free-field radiant exposure levels for the ignition of heavy fabrics. It is implicitly assumed that fuels will be exposed to the free-field level in the range of distances considered (this assumption is strengthened by the choice of highly abundant fuels, particularly those at or near windows-for example, drapes), and also that blast effects, such as collapse of buildings, will not significantly alter the situation at the initial primary-fire perimeter. To keep these assumptions in mind, we might refer to the quantities we are assuming as the "probability of one or more significant fires in and around an exposed, uncrushed, residential building."

An S-shaped curve, the exact shape of which will depend on the actual distribution of fuels of various weights, can be fitted to the points P_1 and P_2 to give the probability of fires at other ranges and calorie levels, as shown in the box in Fig. 9. Typical curves generated by this procedure are shown in Figs. 9 to 12, in which a cumulative Gaussian distribution has been fitted to various assumed probabilities. A somewhat surprising result is the apparent lack of sensitivity of the probability function, at least in the lower altitude cases (Figs. 9-11), to the initial choice of probabilities. Although the probability function for other distributions has not been calculated, it is apparent that for any reasonable distribution, for instance, Poisson or even linear,

* The surveys did not include shingles and other moderately heavy building materials that probably should not be ignored for some situations.

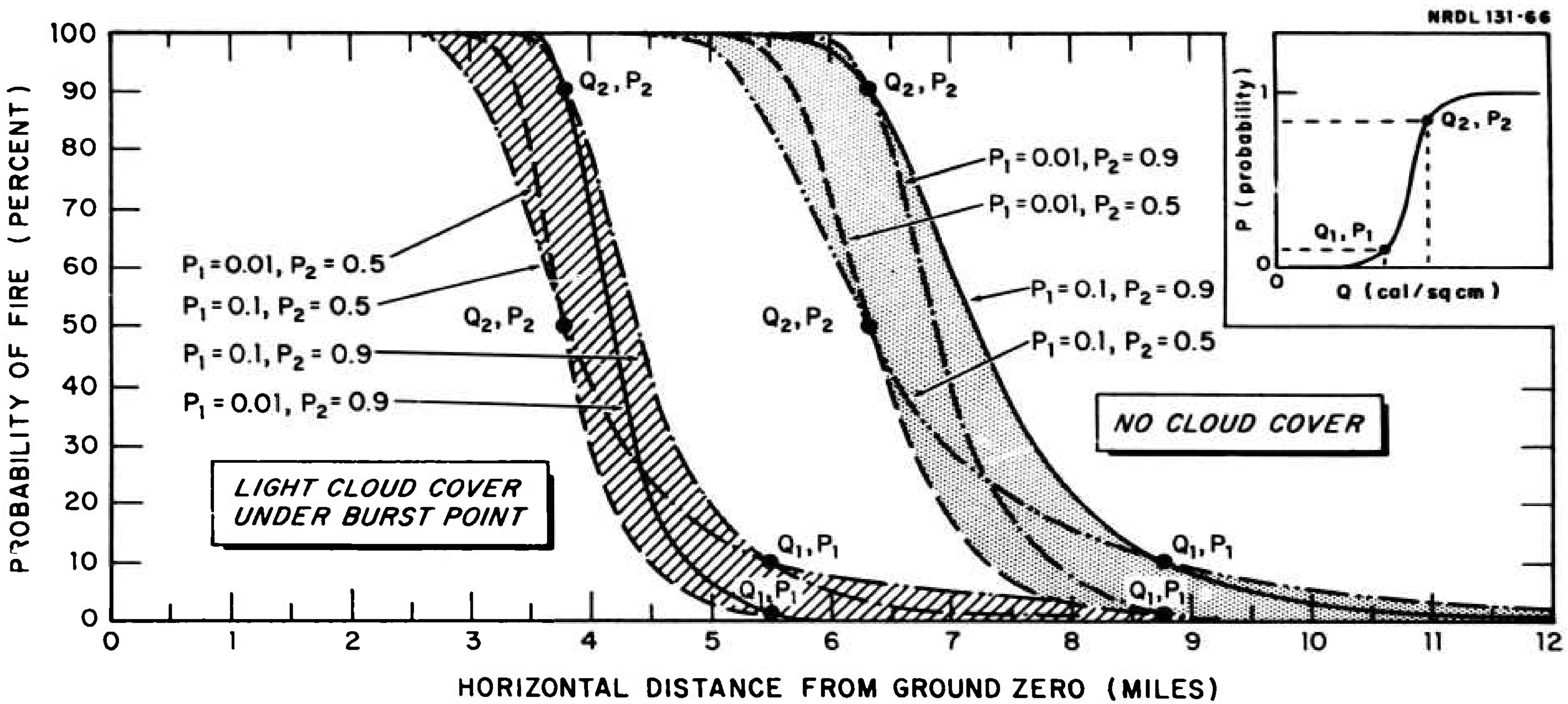


Fig. 9 Probability of Significant Fire in Exposed (Uncrushed) Buildings, 1 MT Burst at 1.2 mile altitude, 12 mile visibility along surface, 50% R.H., for no cloud cover and for light cloud cover under burst point

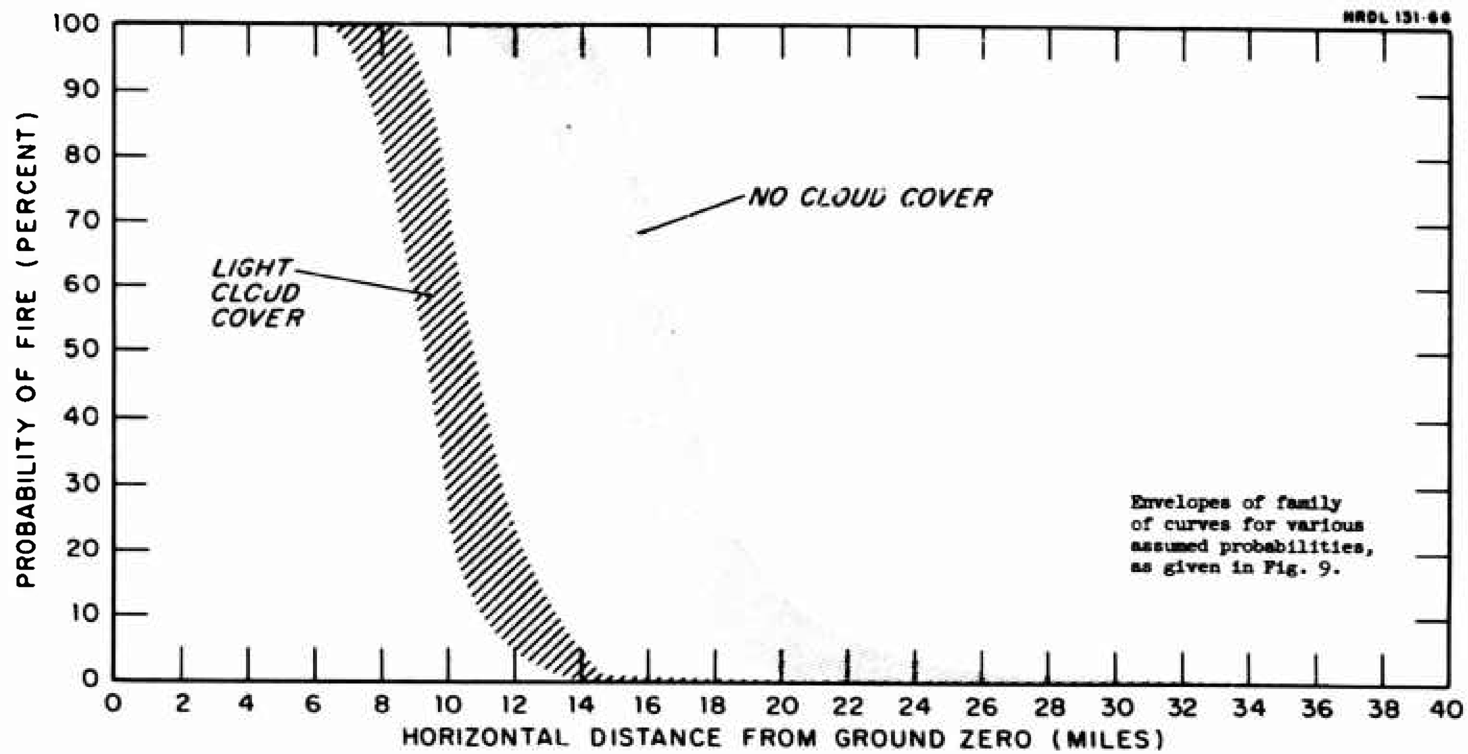


Fig. 10 Probability of Significant Fire in Exposed (Uncrushed) Buildings, 10 MT Air Burst at 2.7 mile altitude, 12 mile visibility along surface, 50% R.H., for no cloud cover and for light cloud cover under burst point

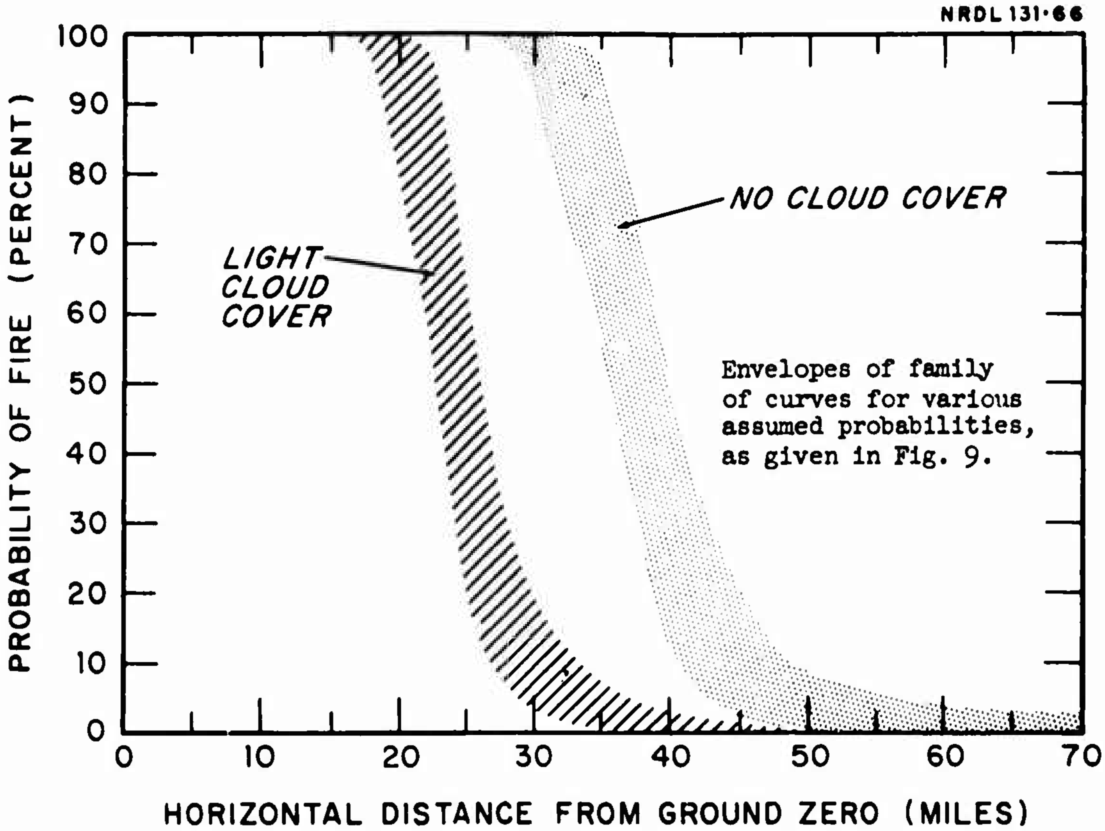


Fig. 11 Probability of Significant Fire in Exposed (Uncrushed) Buildings, 100 MT Burst at 5.7 mile altitude, 12 mile visibility along surface, 50% R.H., for no cloud cover and for light cloud cover under burst point

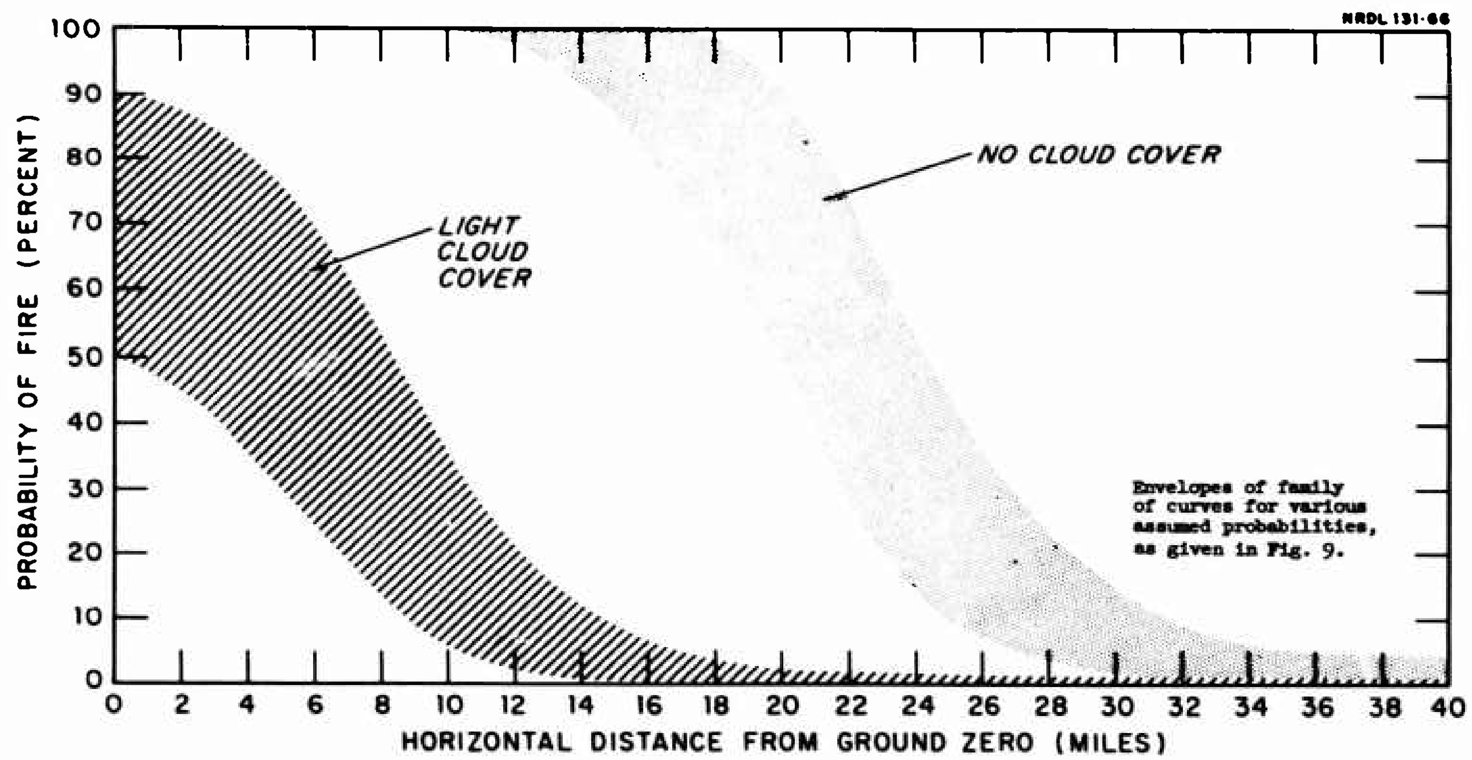


Fig. 12 Probability of Significant Fire in Exposed (Uncrushed) Buildings, 10 MT Air Burst at 15 mile altitude, 12 mile visibility along surface, 50% R.H., for no cloud cover and for light cloud cover under burst point

would not be drastically different.* The distance corresponding to the 50% probability level might be considered to be a measure of the initial primary fire perimeter as long as there is a high concentration of exposed kindling fuels and no more than a modest level of blast damage at that distance. Accordingly, the primary-fire perimeter is a strong function of weapon yield, burst altitude, and the properties of the atmosphere (presence of cloud or haze layers between the burst point and the target).

There is an interesting synergistic interaction between burst altitude and the presence (and altitude) of haze or cloud layers in the atmosphere. If the fireball is below a haze or cloud layer and the atmosphere below the layer is clear, the primary-fire perimeter, as predicted above, is somewhat farther from ground zero than if there is no layer (not shown in figures). Raising the altitude of the fireball increases the primary-fire perimeter at a pronounced rate until the fireball attains the same altitude as the cloud or haze layer. Above that altitude, a sharp decrease in the perimeter occurs.

For the 10-MT example shown in Figs. 10 and 12, the perimeter for a 15-mile burst altitude (chosen to maximize the range of ignition of heavy fabrics) is significantly greater than that for a 2.7-mile burst altitude (optimum for blast damage). However, when there is a light

* A word of caution concerning interpretation of the material: First, the probabilities presented are for fuels that are exposed to the full free-field radiant-exposure levels at corresponding distances and should therefore be modified by a function that takes account of differences between these levels and actual (or realistically expected) levels. Some of these factors are considered in 5.2.2. Second, although the ranges of high fire probability in exposed fuels are not strongly dependent on chosen probabilities or distribution functions for the examples shown in Figs, 9 through 11, the ranges of low probability are sensitive to such assumptions. In situations where thousands of primary ignitions of light kindling fuels may occur per square mile, a 1% probability of a significant fire may have an important civil-defense impact, particularly if conditions are favorable to the spread of fire. Finally, for low air bursts, the nonsensitivity of ranges of high fire probability to probability-value-and-distribution choice is due in large measure to the rapid change in radiant-exposure level with distance. For higher burst altitudes (comparable to or greater than the horizontal ranges considered), the radiant-exposure level on the ground decreases much less rapidly with increasing horizontal range, and accordingly the estimated ranges of high fire probability become much more sensitive to the initial assumptions.

cloud cover under the burst point (for both cases), the calculation predicts a much greater contraction of the perimeter for the 15-mile burst altitude than for the 2.7-mile burst altitude. Furthermore, the uncertainty in range introduced into the latter case by the initial choice of probabilities is virtually unaffected by cloud intervention, whereas for the former case the uncertainty becomes so large that the primary-fire outcome is quite uncertain (that is, mainly low probabilities except in an area of the target where interior fuels would typically be shielded by roofs.)

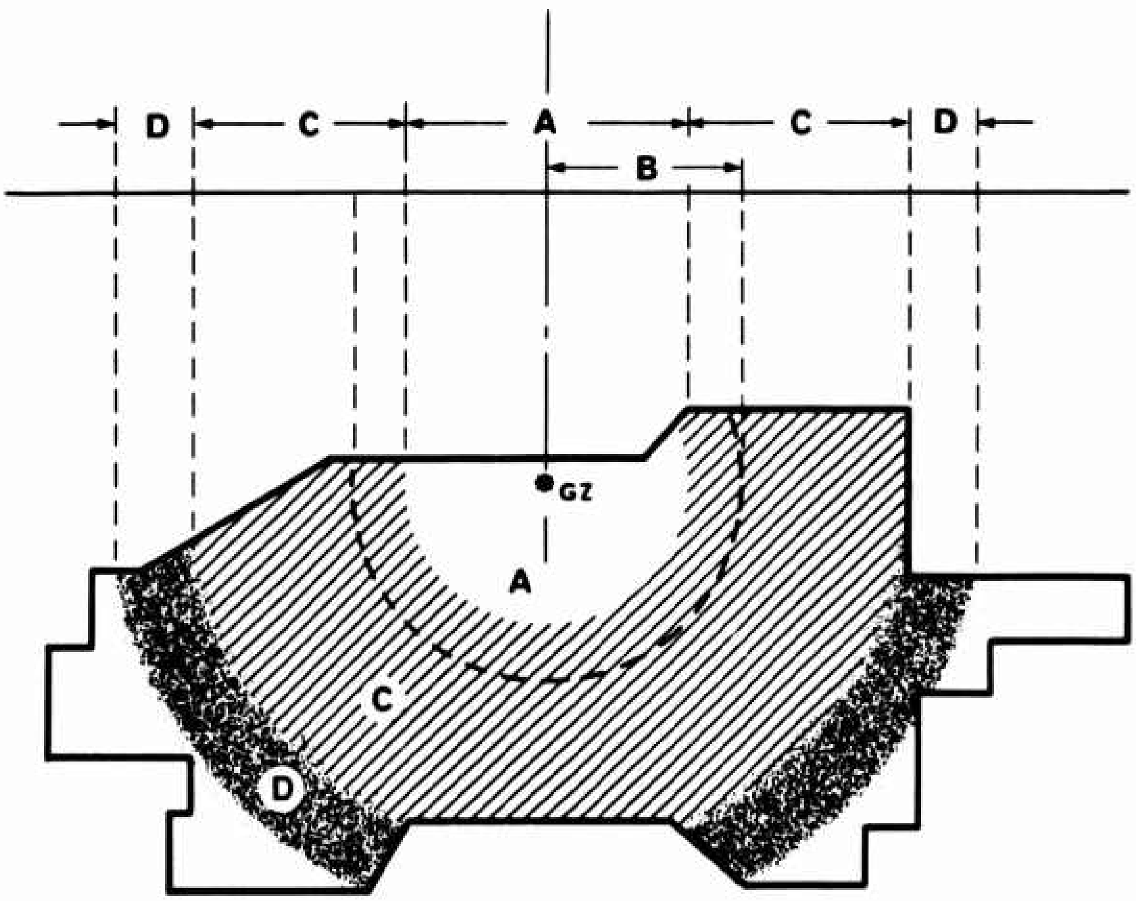
5.2.2 Estimates Taking Into Account the Fuel Field of View and Blast Effects

Although curves such as those shown in Figs. 9 through 12 are useful for analyzing the sensitivity of early fire behavior to parameters that affect it, considerable caution should be exercised in attempting to interpret them for vulnerability-assessment purposes. It has already been pointed out that the probabilities displayed are intended to represent the radial distribution of probabilities of significant fires in and around residential buildings suffering modest blast damage where there is a variety and concentration of kindling fuels representative of residential areas for which fuel surveys have been conducted, and where these fuels are not significantly shielded from a direct view of the fireball or a substantial part of the free-field radiant exposure level at that distance.

If we possessed a complete set of such radial probabilities for all the relatively homogeneous subareas such as we might conceive of an urban target being divided into, we would still have only a part of the information needed for primary fire-vulnerability assessment. In some subareas, such as wildlands and some suburban areas, where exterior fuel concentrations are high and shielding can be disregarded, these radial probabilities may provide adequate descriptions by themselves. In more urbanized subareas, it is necessary to modify these probabilities with additional information about the frequency distribution of exposed fuels and, in some circumstances, to consider the effects of blast before a realistic picture of the initial fire situation can be obtained.

Consider the hypothetical situation (see Fig. 13) of a homogeneous urban subarea exposed to the thermal radiation of a nuclear weapon detonated above the surface at the point marked GZ (Ground Zero). In circular Area A, concentric with the point GZ, having a radius certainly less than the burst altitude,* the only directly exposed fuels of kindling

* This corresponds to large angles between the fireball line-of-sight and the horizontal where shielding such as by eaves etc., prevents exposure of interior fuels.



Area **A** : *Exterior fuels and roofing materials exposed.*

Area **B** : *Collapse of buildings occurs within this area.*

Area **C** : *Annular area; interior fuels exposed through openings facing general direction of burst.*

Area **D** : *Interior fuels generally exposed through upper story windows facing general direction of burst.*

Note: HOB > A/2

Fig. 13 Schematic of Hypothetical Homogeneous Urban Subarea Exposed to Thermal Radiation

weight are exterior fuels and roofing materials. If this area is built-up moderately, exterior fuels are not very abundant (nor do they constitute much of a hazard), and unless there is a very large component of scattered-in radiation, the fire situation in the absence of blast effects would be determined largely by the ignitability of the roofs. Suppose, further, that the blast response of the buildings in this homogeneous area is such that collapse occurs out to a certain distance, B, (which could be larger or smaller than the radius of Area A, depending on yield, burst altitude, and the nature of the buildings) as indicated by the dotted line in the figure. The probable fire behavior in severely blast-damaged areas is discussed in 5.3, but it is clear without knowing the details that the situation within this area will be significantly different from that in more remote areas. In the lined Annular Area C, the angle between the fireball line of sight and the horizontal is such that a significant direct exposure of interior surfaces will occur through windows located anywhere on outside walls facing in the general direction of the burst. In shaded Area D, only upper-story windows are assured of direct exposure, though some lower-story windows may see the fireball (or at least part of it). Beyond D, direct exposure of windows will occur infrequently, and again exterior fuels and some roofing materials will determine what fires may occur (if any). The indistinct lines separating the areas are intended to illustrate the inexact nature of such division even for so-called homogeneous subareas.

Fields of view of interior fuels are determined by a great number of variables, including furniture placement, use of drapes, blinds and awnings, extent of roof overhangs, proximity of adjacent buildings and trees, and housekeeping practices. One very important property of urban targets is that they are inherently anisotropic. Even in the case of such a seemingly homogeneous area as a new (unlandscaped and unmodified), low-cost housing tract built by the same contractor, the exposure of fuels is a strong function of direction. Fronts and backs generally have a much higher proportion of window area than sides do. Also these windows usually face either a street or large yard, and because of the much larger distances to adjacent houses, they see a much greater fraction of the sky than side windows do. It is not unusual for interior fuels with window openings in the front of a house of a low-cost, suburban tract to have a view of the sky that includes angles less than 10° above the horizon. Backyard windows generally "see" less sky near the horizon because of trees, garages, fences, etc. Side windows are frequently limited to sky views over 30° above the horizon.

One interesting result of the free-field calculation of radial probabilities of significant fires caused by low airbursts, the results for which are shown in Figs. 9 to 11, is that, at the predicted primary-fire perimeter, the fireball subtends an angle of approximately 11°, which appears to be virtually independent of yield for the three low-air-burst cases considered (1, 10, and 100 MT). Thus, at the supposed free-

field fire perimeter in a residential area, the fireball typically would be obscured as viewed from window height when the weapon is detonated close to the ground, whereas at burst altitudes chosen to optimize blast damage (roughly equal to the fireball diameter) only about half of the fireball could be seen from the windows described above as having the fullest sky view.* Therefore, under these circumstances, the actual fire perimeter would probably be determined more by the field of view than by free-field ignition radii. For greater burst altitudes, the fire perimeter would expand rapidly with burst altitude, because of the general improvement in field of view, atmosphere transmission, and ignition efficiency of the shortened thermal pulse, until the increased slant path and/or intervention of clouds or haze reverses the trend. The preceding discussion has been confined to a narrowly limited case of residential areas, but many, if not most of the principles can be applied generally.

5.2.3 Reliability of Estimates and Ranking of Parameters

Stochastic estimates of the distribution of significant primary fires over an urban target can probably be made reliable if a great deal of attention is given to dividing the target area into homogeneous subareas and if proper account is taken of the variation in fuel field of view with distance from ground zero. Basically, the same parameters apply here as in the previous discussion in 2.2 of the actual distribution of ignitions, since the nondetailed, stochastic estimate of significant fires is merely an extension of that subject. Additionally, we are concerned here with (1) "parameters" that describe the choice of probability of sustained fire corresponding to ignition of certain abundant fuels, (2) the choice of a probability function relating probability of sustained fire and radiant exposure level, and (3) the interaction of blast effects with the generation of significant fires. No fundamental parameters related to the foregoing ill-defined "parameters" have as yet evolved.

5.3 DISTRIBUTION OF SIGNIFICANT FIRES OVER URBAN TARGET BY DETAILED ANALYSIS

5.3.1 Dependence on Detailed Knowledge of Fuel Distribution Relative to Primary Ignitions

It is reasonably well established (see App. F) that the ignition of a major item of furniture (a couch or a bed) in a moderately sized residential room will lead to full fire involvement of the room in a short time if firefighting action is absent. It seems safe to assume that, if a definite amount of heat (suitably concentrated in space and time as determined by room dimensions and structural features) is released in a room, the room will become involved in fire. This assumption is the basis of some definitions of a significant fire in terms of an "incendiary equivalent" (see 5.1). Attempts to evaluate the properties of the heat

* See footnote on p. 42.

source have been made using data derived from incendiary bombing experiences.

The concept can be used as a basis for a detailed analysis of significant-fire distributions following nuclear attack. After analyzing the detailed distribution of primary ignitions, as described in 2.2, one would determine how many fires of "incendiary-equivalent" magnitude would result either by direct primary ignition of large fuel items or by propagation of fire to them from proximate lighter fuels. Thus, it is necessary to know what fuel items in a room represent an "incendiary equivalent" for that room, whether they are likely to be ignited directly by the thermal pulse of a nuclear weapon detonated under a particular set of circumstances, and if not, what fuels in the room will be ignited and whether they are suitably located relative to the other fuels in the room such that fire spread from item to item will generate a fire of "incendiary equivalent" magnitude.

For the cases where ignition of large fuel items is assured, the analysis is little, if any, more difficult than the analysis of primary-ignition distributions. For the kinds of operational problems requiring a high-reliability, conservative estimate of fire damage, the analysis of urban "incendiary equivalents" can be a satisfactory endpoint for fire-damage assessment. Results would probably not be significantly different from those obtained from stochastic estimates of the initial primary fire perimeter.

For civil-defense purposes, however, more information is required. Although the actual range of the initial primary fire perimeter may not be greatly different from the range over which heavy fuel items ignite, the subsequent stages of fire development and spread are of vital interest to civil-defense planners, and analysis of the later stages will depend heavily on a detailed knowledge of initial fire distribution.

To analyze cases of potential fire development where only light kindling fuels (incapable <u>by themselves</u> of generating a significant fire) are ignited by the thermal pulse, we require not only a much more extensive list of data on fuel types and distributions than we need for primary-ignition purposes,* but we need to know how fire propagates itself from fuel item to fuel item.

* Data on (1) location of fuels by type relative to one another, (2) heat release and heat-release rates of fuels by types, (3) amounts and kinds of pyrolysis and combustion products, and (4) dimensions and structural features of the enclosure, if any, including sources of ventilation, etc.

5.3.2 Dependence on Factors Affecting Item-to-Item Propagation

The mechanisms of fire propagation from fuel item to fuel item are treated in some detail in Appendices D and F. Some information is available on spread of fire through fuels in contact, but next to nothing is known about propagation between separated items (on this scale where radiation or convection is not clearly the dominant heat-transfer mechanism). Some of the factors that are probably important are (1) burning rate, (2) heat-release rate, (3) relative location, (4) relative amounts of radiation and convection, (5) air velocity and direction, (6) collapse of burning fuel items, and (7) environmental factors, such as air temperature, oxygen supply, and combustion product accumulation. This subject receives more attention in Section 7.2

5.3.3 Reliability of Estimates and Ranking of Parameters

Detailed estimates of the distribution of significant primary fires over an urban target are not feasible at the current state of knowledge due primarily to gaps in information concerning fuel types and distribution, and the mechanisms of item-to-item propagation (build-up). The following appear to be the determining parameters in approximate order of sensitivity for fire vulnerability: (1) distribution of fuels by type, (2) the number of "incendiary-equivalents" exposed by thermal pulse, (3) the factors governing item-to-item propagation: (a) heat-release rate, (b) burning rate, (c) relative location of items, (d) relative amounts of radiation and convection, (e) air velocity and direction, (f) collapse of burning fuel items, and (4) environmental factors such as air temperature, oxygen supply, and combustion product accumulation, and (5) the distribution of "incendiary-equivalent" magnitude fires.

SECTION 6

PARAMETERS DETERMINING PROPAGATION OF EXTERIOR FIRES TO BUILDINGS AND OTHER STRUCTURES

6.1 STRUCTURES WITH PROXIMATE TRASH ACCUMULATION AND FUEL STORAGE

6.1.1 Weather Factors

Relative humidity and precipitation have a retarding effect on both rate of spread and burning intensity of exterior fuels. These, in turn, are expected to be determinants on whether exterior fuels will ignite structures. If trash and other fuel accumulations are large, the fire may grow to an intensity great enough to offset the retarding effects; but such offsetting would not usually be the case where substantial precipitation is involved. Wind markedly enhances the rate and intensity of burning and can carry burning fuels against structures, through openings, and into fire-susceptible locations, such as under eaves and onto roofs. In a nuclear attack situation, window panes will be broken by blast, and the blast wave, natural winds, and fire-generated winds could transport burning fuels through the open windows into unignited interiors.

6.1.2 Structural Factors

It is a rather common thing to find buildings in warehouse areas with attached wooden ramps and platforms against which trash and other combustible items have accumulated and on which combustible packaging materials are stored. This set of circumstances is ideal for fire spread to the building. A great variety of fire-susceptible structural features can be found in any urban area. Some of these are discussed in Appendix A.

6.1.3 Housekeeping Practices

This point needs little amplification. Obviously, good housekeeping practices reduce the fire hazard from exterior ignitions to a minimum.

6.1.4 Fuel Factors

The amount of exterior fuel is a major determinant of whether exterior fires will propagate to proximate buildings. The large amount of exterior fuels required to propagate a fire to sound wooden structures has been demonstrated experimentally (see App. F). As a result, it is commonly held that the exterior fuels in built-up urban areas do not constitute much of a hazard except for particularly susceptible structures, such as warehouses, and for cases of high winds.

6.1.5 Approximate Order of Parameter Sensitivity

The following appear to be the determining parameters in approximate order of sensitivity for fire vulnerability: (1) location and amount of exterior fuels relative to fire-susceptible structural features in certain buildings, (2) precipitation, (3) wind speed and direction relative to location of proximate fire-susceptible structures, and (4) relative humidity.

6.2 STRUCTURES WITH COMBUSTIBLE EXTERIORS

6.2.1 Weather Factors

Ordinarily combustible exteriors of buildings do not achieve sustained burning by exterior non-building fires under the best of conditions. The continued burning of those materials that are marginally capable of being ignited, such as shingles and asphalt-impregnated felts, would be heavily dependent on all weather factors. High insolation levels would enhance their fire-propagating potential, whereas high relative humidities, precipitation (either current or recent), and wind would limit or extinguish them.

6.2.2 Structural Factors

The exteriors of structures that achieve sustained burning from the thermal pulse will generally involve entire structures by igniting interior combustibles. Commonly, this involvement will result from the penetration of structure enclosures (through newly formed openings) and/or by the direct propagation through openings (all kinds) of hot gases, sparks and radiation. Propagation from initial burning sites will be aided by their appropriate location relative to openings and to fire-susceptible structural features (eaves, under shingles, trim, finish, etc.). Fire-susceptible features of structures are often associated with areas of local "roughness" on the exterior of structures. These areas enhance the likelihood of fire propagation to interior fuels because they tend to locally conserve heat (by shielding or protecting from wind and convection currents). The upper parts of urban structures (upper stories, building roofs, etc.) are more likely to be involved, since the location of the exterior initial sites of sustained burning will

depend on direct exposure to thermal radiation. Fire penetration (may-be by collapse) from exterior structural fuels to interior fuels will depend on the continuity of combustibles and/or spaces enroute to the interior (insulation in open construction spaces can halt or hinder penetration through walls) and on fuel factors and the weather. Direct propagation through openings will depend on the location, number and size of openings relative to the location of exterior sustained ignitions and the ability of these ignitions to create sparks, firebrands, and hot gases (parameters of fuel and finish) that can subsequently pass through the openings. The susceptibility of interior fuels to ignition is discussed in Section 7. New openings contribute to the propagation. They result from the disrupting effect of the blast wave on structures and from the effects of the blast wave on existing opening covers (for example, breakage of glass in windows). The larger number of openings increase the ventilation and susceptibility of the entire structure to fire.

6.2.3 Housekeeping Practices

Good housekeeping can minimize the likelihood of fire propagation from the burning combustible exteriors, The number of openings in dilapidated structures can be reduced (for instance, by nailing down loose boards), and the number of fire-susceptible locations can be reduced (for instance, by tabs on asphalt shingles that prevent lifting in a strong wind).

6.2.4 Fuel Factors

The propagation of fire from exterior ignitions on structures is strongly dependent on the amount, geometry (thickness and surface areas), degree of combustibility, and the proximity interrelations with noncombustibles (or items of low degree of combustibility) of combustible exterior fuels.

6.2.5 Approximate Order of Parameter Sensitivity

The following appear to be the parameters in the approximate order of sensitivity for fire vulnerability: (1) location of the exterior sustained burning on structures, (2) combustibility of proximate fuels, (3) wind speed and direction, (4) "heat-conserving" properties of fire-susceptible locations (construction features), (5) size and location of openings, (6) weather factors, and (7) housekeeping.

6.3 STRUCTURES IN HEAVILY VEGETATED AREAS

6.3.1 Weather Factors

The susceptibility of vegetative fuels to ignition by the thermal pulse of a nuclear burst, and to subsequent fire build-up and spread, is strongly dependent on weather factors (recent and current). Relative

humidity and wind speed appear to be the more important weather parameters. The transport of burning vegetative fuels to fire-susceptible locations of structures is dependent primarily on the speed and direction of the wind, and the characteristics of firebrands.

6.3.2 Structural Factors

Fire spread from heavily vegetated areas to structures will depend on the continuity of vegetative fuels to the structures without appreciable winds and on the distances firebrands must be transported to the structures with winds of proper speed and direction. The topography (slope, aspect, and direction) appears to influence the above effective distances. Light vegetative fuels are more readily ignited and can involve the heavier vegetative fuels. The latter produce heavier firebrands, which are more likely to ignite the less combustible exteriors of structures.

6.3.3 Housekeeping Practices

Good housekeeping will minimize susceptibility of structures located in heavily vegetated areas. Examples are the plowing, preburning, pruning of firebreaks around structures (which increases "jump" distances and breaks the continuity of the fuel bed), the removal of fine fuels, and the reduction of the number of susceptible locations of structures.

6.3.4 Fuel Factors

Heavy fuels (trees and bushes) and light fuels (grass, leaves, needles) undergo changes with season, age, soil conditions, and weather that govern the susceptibility to primary ignition and the capability of subsequent spread to structures.

6.3.5 Approximate Order of Parameter Sensitivity

The following appear to be the determining parameters in approximate order of sensitivity for fire vulnerability: (1) proximity of vegetative fuels to fire susceptible locations, (2) susceptibility to the formation of firebrands, (3) weather factors (wind speed and direction, snow cover, relative humidity, and precipitation, recent and current), (4) topography, and (5) housekeeping practices.

SECTION 7

PARAMETERS DETERMINING SPREAD OF INTERIOR FIRES IN BUILDINGS AND OTHER STRUCTURES

7.1 ESTIMATES THAT DO NOT TREAT MECHANICS OF PROPAGATION

7.1.1 General

In this subsection, we consider assessment procedures that attempt to estimate the number and distribution of buildings and other structures that initially will become involved in fire as a result of propagation from interior ignitions, without analyzing in detail the sequence of steps: (1) primary ignition; (2) fire initiation and fire build-up in rooms of primary ignition; (3) penetration of walls, and room-to-room propagation, and (4) total fire involvement of the structure. A useful starting point is a knowledge (or stochastic estimate) of the number and location (or the probable distribution)of significant fires, as discussed in Section 5. We begin by summarizing the pertinent material of Section 5 and relating it directly to the objective of this subsection.

7.1.2 Probability That Significant Fire will Result from Ignition; Stochastically Described Target

In a target area described in a stochastic way, the probable distribution of significant fires can be predicted from free-field ignition radii of abundant fuels in each of the "homogeneous" subareas of the target. Such estimates are likely to be unrealistic because they ignore shielding and subsequent blast effects. Improved estimates should result from procedures that take into account fields of view of interior fuels and blast responses of the structures in the subarea as functions of distance from surface zero.

7.1.3 Estimates of Significant Fires for More Deterministically Described Targets

Analysis of targets described deterministically in some degree requires (1) the selection of fuel items that, when ignited, will by themselves generate a significant fire, and (2) the deduction of likelihood that these fuel items will be ignited either directly or indirectly. The degree of sophistication will depend on the detail to which the

target is described, from typical cases (fuel types and fields of view) for different kinds of rooms in various classes of buildings on the one hand to determined locations and fields of view of fuel assemblies on the other.

7.1.4 Probability that a Significant Fire in a Structure will Lead to "Total Involvement" of the Structure

Depending on the approach taken, not only the relationship of the probability of building involvement to the probability of occurrence of significant fires, but also the definition of a significant fire itself will be subject to considerable latitude of choice. For example, it would be very convenient when dealing with a target described on a purely stochastic basis to define a significant fire as a fire that has a high probability of leading to "total involvement" of the entire structure associated with it. Accordingly, a significant fire for one class of structures (those in a given "homogeneous" subarea) would differ from those for other classes. This difference, however, introduces no serious complications into a procedure that glosses over details by semi-intuitively relating the ignition of abundent fuels in each subarea to some characteristic "fire outcome" based on past fire experience.

For more deterministically described targets, at least two different combinations of significant-fire definitions and probabilities for "total involvement" can be readily conceived. In one approach, a significant fire can be based on the ignition of an "incendiary equivalent" of fuel (as described in Sec. 5.1) and the probability of either room involvement or building involvement can be deduced from data on conventional incendiary-warfare experiences and structural details of the room and/or building having the one or more ignited "incendiary equivalents" of fuel. Another approach defines a significant fire as a fire that will very likely lead to flashover (or other forms of total room involvement) of the room in which it occurs. In this case, the characteristics of the significant fire are dependent on the dimensions and structural features of the room (or other enclosure). Further discussion of the relationships between size and other fire characteristics and the features of the enclosure that will cause a flashover is in 7.2.

7.1.5 Probability that Total Building Involvement Follows Total Room Involvement

Non-mechanistic procedures of analysis, which define significant fires in such a way that flashover (or other forms of total room involvement) may be deduced, require additionally some provision for evaluating the probability that a structure containing a "flashed over" room will itself become "totally involved" in fire. Once again, the only available source of information on which we may base the analysis, if it is to be more than a subjective guess, is fire experience. Parameters that appear

to be important are the structural features of the building and the location of the room (or rooms) initially involved. Interaction of blast should not be ignored, particularly if considerable loss of structural integrity is anticipated.

7.1.6 Reliability of Estimates and Ranking of Parameters

In this subsection, a wide range of nonmechanistic approaches have been discussed. Correspondingly, the resulting estimates of initial fire involvement of the structures in a target area will range in reliability and output detail from the minimal level for stochastically described targets (possibly misleading if fields of view are not taken into account) to variably better levels for more deterministically described targets, depending on the amount of detail in the description. One very important difference in output information is the amount of information pertaining to time dependence. The more stochastic approaches provide only an estimate of an "initial state," which might be interpreted as the distribution of burning buildings during, say, the first half hour after the nuclear burst. More detailed descriptions of targets permit treating the progression of fire from the initially flashed-over rooms throughout the building in a timewise fashion. The best temporal fire growth information is realized from an analysis that treats the mechanics of fire propagation. (This subject is discussed in 7.2.)

The factors (in approximate order of importance) that affect nonmechanistic estimates of initial building fires include: (1) choice of definition of "significant fire," (2) choice of fuels that will generate a "significant fire" if ignited or choice of probability that a "significant fire" will result from the ignition of abundant fuels, (3) fields of view of windows in structures, (4) fields of view of fuels in structures, (5) dimensions of rooms, (6) details of room construction and contents, (7) location of room in structure, and (8) details of structure.

7.2 DETAILED, MECHANISTIC EVALUATION OF FIRES IN STRUCTURES

7.2.1 Dependence on Detailed Knowledge of Structural Features and Fuel Contents

The prerequisite to a detailed, mechanistic evaluation of fires in structures is a detailed knowledge of the structural features and the fuel contents of each room (or other enclosure) which constitute the structure. Inasmuch as we have already discussed procedures for estimating the actual distribution of primary ignitions following a nuclear burst, let us begin here by enumerating the data we need on ignited fuels. Primary ignitions will ordinarily occur in interior fuels that are, or have as components, relatively thin elements. If the ignited element is in contact with a substantial fuel complex or part of it, fire can propagate from the light fuel to the heavy fuel, and a serious fire may result. Even when they are not in contact, propagation may occur with

suitable orientation of ignited and unignited fuels. A bedspread is a readily ignited fuel and once ignited is quite likely to set the whole bed on fire. Papers on a desk are quite susceptible to ignition, but they are not likely to cause the desk to burn unless there is a large quantity of them or they are under a wooden shelf or some other relatively lightweight combustible appendage to the desk. It is apparent that we need to know something about the size, heat release, burning behavior, and location of ignited fuels. Some of the factors that affect the heat release and burning behavior are (1) the thickness, composition, shape, orientation, and proximity of other burning fuels, (2) windows and other sources of ventilation, (3) walls, and other boundaries, and (4) the humidity, combustion-product content, temperature, and other characteristics of the ambient "air" around the fuel. These factors are discussed in more detail in App. D.

7.2.2 Detailed Knowledge of Unignited Fuel Contents of "Room"

Generally we need similar information on the unignited fuels in the room or other enclosure, namely, location, size, fuel value, and burning behavior; but also we need information that will allow us to estimate the susceptibility of the fuel to ignition by adjacent burning fuels. Thus, we need to know (1) the fuel's location relative to ignited fuels, other unignited fuels, windows, doors, walls, (2) its size, shape, composition, and orientation, and (3) the characteristics of the ambient "air."

7.2.3 Dependence on Structural Features of Enclosure

The growth of fire in an enclosure depends on the dimensions of the enclosure, amount of ventilation (at later stages at least), and the insulating properties and fire behavior of the walls of the enclosure. Windows and other openings must be considered in terms of their sizes relative to the fuel contents and dimensions of the enclosure, and in terms of their location in the enclosure.

7.2.4 Mechanisms of Fire Initiation and Buildup

This subject is treated in considerable detail in Appendices D and E. Some work has been done, but much research remains to be done before the mechanics of item-to-item propagation of fire, the mechanics of and conditions for flashover, and the temporal sequence of events will be understood well enough to permit descriptions of fire behavior to be made in a general way.

7.2.5 Mechanisms of Penetration and Room-to-Room Spread

This subject, like the previous, is not well understood although some usable information does exist. Factors bearing on it include (1) location of room (or rooms) of initial fire involvement, (2) penetration

times of the structural barriers (walls, doors, etc.) separating the various rooms and enclosures, (3) fire-propagation behavior in halls and stairwells, and (4) building ventilation (including wind).

7.2.6 Blast Effects

Blast can either enhance or inhibit the development of fires in structures. In regions of low peak overpressure, it will at least open windows and doors and in many cases will cause partial collapse of walls, ceilings and roofs. These effects will increase both the fire susceptibility of structural fuels and the ventilation. These, in turn, will enhance fire development except, perhaps, in situations where conditions are no longer amenable to flashover, though it is not at all clear at the present how much of a factor such conditions might be.

At higher peak overpressures, blast will cause the general collapse of structures, which will drastically alter the fire situation. If blast collapses buildings having a large nonfuel-to-fuel ratio, incipient interior fires will quite probably be snuffed out. Buildings of more generally combustible construction may continue to burn, but the burning behavior, though it should be very different from that of an uncrushed structure, is not predictable, even in principle, without a detailed knowledge of blast-induced structural changes.

There is some evidence, albeit inconclusive, suggesting that primary fires may be extinguished by blast (from weapons in the megaton range) if peak overpressures exceed about 5 psi (see App. E. 2.7). Of course, in many cases the accompanying wind will fan the fires to more intense levels of combustion and translate small ignited objects into areas of unignited, blast-created kindling. To some extent, at least, the fires that may be extinguished will be offset by fires caused by blast. Everything considered, it seems that the area of severe blast damage is also an area of high fire likelihood.

7.2.7 Reliability of Estimates and Ranking of Parameters

If estimates of fires in structures could be made with a first-principle, mechanistic approach (and at the present state-of-the-art, they cannot), they would be the most reliable of all possible estimates. The vulnerability of structures to primary fires is determined by the same parameters that determine the actual distribution of primary ignitions over the target (with the same sensitivity); but in addition vulnerability depends on (1) factors that describe the location and fire-propagating potential of proximate unignited fuels, (2) the environment, (3) the (as-yet-not-well-understood) processes of item-to-item propagation, (4) fire buildup, room-to-room propagation, and (5) under some circumstances, blast effects. Because of the complexity of the problem and the rudimentary level of understanding of it, only the most superficial listing of parameters is possible.

SECTION 8

FIRE-SPREAD RATE, DIRECTION, AND EXTENT

8.1 GENERAL

This section pertains to the phase of fire vulnerability that begins with the initial pattern of established fires and treats the history of growth and change of the area involved in fire. As in previous sections, there is more than one way to analyze the problem. Starting with a stochastically predicted, initial fire perimeter or a deterministically derived distribution of structural fires and major exterior fires, fire spread can either be surmised from past fire experience or it can be calculated mechanistically. The choice, as in Section 7, is dictated both by the amount of detail with which the target is described and the state of knowledge of fire-spread mechanisms.

8.2 ESTIMATES BASED ON FIRE EXPERIENCE

The propagation behavior of fires in the open in determined by four basic groups of parameters: fuel, weather, topography, and thermomechanical properties of the fire. To avoid a mechanistic treatment of fire spread, the last group is treated only implicitly by categorizing observed fires as large or small, urban or wildland, line or area, intense or feeble, etc. A little reflection on the causes and effects of the fires characterizing each of these categories reveals a strong synergism of each of them and of fuel, weather and topography. Some of the interactions and their implications in mass fires are discussed in Section 9.

When we attempt to predict fire spread on the basis of past experience, we relate the characteristics of the fire at some early instant (for example, the initial fire) to comparable fires for which spread data are available and account for fuel, weather, and topographic parameters to the degree that empiric relations for observed fires permit. Appendix F discusses a variety of fire-spread models that depend on data derived from fire experience. In general, these models utilize two or three "behavioral parameters" (for instance, a "spread parameter" and a "decay parameter"), which are functions of the basic variables of fuel, weather, and topography. The major obstacle to applying fire-spread models for fire-spread predictions (assuming we can reliably describe the initial fire situation) is the derivation of the functional relationships between

"behavioral parameters" and the basic, environmental parameters on which they depend.

8.2.1 Parameters Controlling Fire-Spread Behavior

Parameters that appear to exercise significant control of fire-spread behavior are discussed in the following subsections.

8.2.2 Initial-State Parameters: Fire Fronts and/or Distribution of "First Generation" Fires Temporally and Spatially

Fire-spread history in any given case will depend greatly on (1) the initial state of the fire, (2) the area involved, (3) the density of fires over the area, (4) the locations of fire fronts, (5) the rate of "build-up and burn-out" of buildings, (6) the fuel concentrations initially set afire, etc. Methods for assessing these initial conditions are discussed in Section 7. The amount of output detail will vary from a roughly circular fire perimeter, which conveys practically no temporal and little spatial information, to a detailed pattern and history of "first-generation" fire behavior. The detail with which fire spread can be predicted will depend, therefore, on the method chosen for characterizing the nature of the initial fire, but such detail will also be limited by the deterministic level of description of the areas into which fire may spread.

8.2.3 Fuel Parameters

Fundamental fuel parameters are (1) type (characterized by (a) composition, (b) density, (c) size, (d) thickness, (e) subdivision, (f) age, and (g) factors that determine (a') ignitability, (b') burning time, (c') heat release, and(d') the translatability by wind and buoyant forces, etc.), (2) concentration (per unit volume and area), and (3) moisture content (which depends on weather parameters and local environment).

Available data on urban-fire experiences show no significant correlation between fuel type or moisture content and rate or extent of spread. But this does not necessarily mean that they are independent of one another; rather the data are inadequate to quantitatively show any dependence. There is reason to believe that ground spread rates in extensively built-up urban areas are not sensitive to fuel moisture, but under some circumstances, spotting-jump rates (rate at which fire spreads due to firebrands) and spread limits may be. (See Weather Parameters, 8.2.4.) We anticipate a dependence of spread rate on fuel type (particularly on type of construction; e.g., wood-frame, masonry, single and multistory, external covering, number and sizes of windows, etc.); but again, the lack of data, together with the inherent inseparability of building type and building density, prohibit evaluation of this dependency.

A definite correlation does appear to exist between rate of spread and building density, and certainly building density is a major factor in determining the ultimate extent of spread. The basic parameters that describe building density are the ground area covered by buildings and the separation distances between buildings. Intuitively, we expect fuel load to be a determinant of urban fire-spread behavior. No general relationship has been found to correlate the limits of spread of documented major fires with any of the foregoing parameters, though it has been shown to be strongly dependent on building separation (see App. F). An unexpected result of this correlation is the increase in rate of spread with decreased building density. This inverse relation may be due to the greater frequency of spotting jumps (which are related to type of exterior fuels--kindling, roofing, etc.) sparks, firebrand production, and related ground-spread events that might be expected for areas of low building density.

Rural fire-spread data are inadequate to show significant effects of fuel type and concentration, though there is ample reason for believing these effects exist. A discussion of rural fire spread data is included here because of its greater availability. Rural fuels are generally more continuous in nature than are urban fuels. (By rural fuels we mean primarily vegetation as it occurs naturally in wildland areas and some suburban areas, and as it is grown in the fields and orchards of rural and suburban areas and in the parks of urban areas.) Experimental burns of relatively uniform, continuous fuel arrays as well as theoretical considerations of fire behavior in such fuel arrays, indicate some dependence of fire spread rate on fuel type and a strong dependence on concentration. When weather conditions (and related fuel-moisture levels) are right for spread, a rural fire spreads until it encounters a fuel discontinuity. The limits of spread are clearly dependent on distances separating the relatively continuous areas of rural fuels.

Rural fuels can be described in a moderately detailed, deterministic way without an excessive expenditure of effort, but it is generally not feasible to describe urban fuels in any but the most stochastic fashion unless the area of interest is small.

8.2.4 Weather Parameters

Of all the weather parameters, rate of fire spread appears to be most strongly influenced by wind. Data gathered from actual urban (and rural) fires indicate a roughly linear increase in rate of spread with wind speed except for fires spreading against the wind. (Experimental data for fires in uniform beds show more of an exponential dependence on wind speed.)

Rates of urban fire spread in still air typically range from a few hundredths to a few thousandths of a mile per hour, depending upon building density. Spreading occurs preferentially in the direction of the wind, and the occurrence of spotting is a rather strong function of wind speed and direction. Increases in rate of spread are not clearly delineated for different areas of building density, but something like a doubling of still-air spread rates may occur in the direction of a 20-mph wind, and a tripling with 40 to 50-mph winds.

Humidity, precipitation, and air temperature are joint determinants of fuel moisture, and their influence on fire-spread behavior is essentially limited to that indirect role. Thus, for urban fuels, which are to a large extent protected from the elements, the extent of fire spread is virtually unaffected by humidity and only weakly dependent on precipitation.

The dryness of urban fuels appears to have only a small effect on rate of spread, though it may be significant for spread by spotting. Since spotting appears to be relatively more important than ground spread for areas of low building density, the dryness of roofing materials may be an important parameter to rate of fire spread through the less highly built-up urban districts (for example, residential areas).

Rates of spread in actual rural fires do not seem to be affected by winds of less than 5 mph. Rates of spread in still or nearly still air average only 0.02 mph (30% to 45% relative humidity) but increase about 0.02 mph in the direction of the wind with each 10 mph increase in wind speed. The rate is a fairly strong function of wind direction and appears to be somewhat reduced when the fire is spreading against a moderately strong wind. Rates of rural fire spread on the ground seldom exceed 0.1 mph. Spotting could cause higher overall rates of spread under some conditions. The occurrence of spotting is dependent on wind speed; and although spotting occurs only in the direction of the wind, there is no evidence that rate of spread by spotting is sensitive to wind speed. There is a strong dependence of extent of rural fire spread on wind speed (see "no-spread criteria" and "stopping rules" in App. F).

Fire-spread behavior in rural fuels shows a strong dependence on humidity and precipitation. Rates of spread are sensitive to relative humidity except for cases of high wind velocity. Extent of spread is extremely sensitive to precipitation and shows a moderate to strong dependence on humidity (see "no-spread criteria" and "stopping rules" in App. F).

The properties of the atmosphere over the urban fire area could well influence fire-spread behavior, but no quantitative information is available to allow evaluating this factor. Weather parameters can be deterministically described for many applications (see App. A).

8.2.5 Topographic Parameters

The main topographic parameters are slope, elevation, and aspect. The only fire-experience data available are those on slope as it affects rural fires. Although this parameter is expected to have the greatest effect of the three, data on rates of spread reveal no significant dependence on slope. Topographic parameters can be deterministically described, and in general, it is practical to do so.

8.2.6 Reliability of Estimates and Ranking of Parameters

Estimates based upon fire experience are among the most reliable (if not the only ones) available at the present state of knowledge. Rates of spread through both rural and urban areas are available as indicated above. In approximate order of sensitivity, the parameter groups affecting urban fire-spread behavior estimates based on fire experience are (A) fuel parameters: type, concentration, and moisture content; (B) weather parameters: wind, relative humidity, precipitation, and air temperature; and (C) topography: slope, aspect, and elevation. Topography has no demonstrated effect on available urban spread-rate data. In cases of severe meteorological phenomena, weather parameters can be more important than fuel parameters.

8.3 ESTIMATES BASED ON HEAT TRANSFER AND FLUID MECHANICAL PROCESSES

8.3.1 General

If the target is described in considerable detail and if we have successfully established the detailed pattern and history of the "first-generation" fires, we may wish to treat the thermomechanical characteristics of fires along with the fuel, weather, and topographic parameters so that we might obtain the greatest possible detail in our assessment of fire spread. Even if it is infeasible to characterize the target on a building-by-building basis, or the initial fire in a deterministic way, there is still ample justification for a mechanistic approach to fire-spread evaluation. We can conceive, for example, of an average-city-block or average-city-section description in terms of parameters that affect fire spread and of an analysis of "first-generation" fires based on probability, followed by a mechanistic evaluation of fire spread that would proceed via a stochastic route, such as a Monte Carlo calculation using probabilities of spread based on observed spread mechanisms. The objective here is to consider the parameters that govern the mechanics of fire spread. Background information is presented in App. F.

8.3.2 Radiation Heat Transfer From Burning Buildings

Following the buildup of fire in a structure but preceding collapse, its radiating characteristics are determined by (1) the dimensions of

outer-wall openings of rooms and other enclosures heavily involved in fire, (2) the geometry of flames issuing from the openings and flames issuing from the roof if roof penetration has occurred, (3) the areas of burning exterior fuels, and (4) the temperatures and radiant emittances of flames and glowing solid fuels.

All of the radiation processes in a burning building will not, in general, reach a maximum or constant level of activity at the same time. In fact, some may be well into decline before others are well started. For some classes of structures, such as multistoried, masonry-interior buildings, the radiation output may be governed by the openings (windows, doors, etc.) and radiation may be passing through only a fraction of them at any one time, particularly where primary fires are limited to upper stories. Other classes of structures (for example, wood-frame residences) though they would typically have a much briefer burning time, would not ordinarily approximate a steady radiant source. The spatially averaged radiant intensity of a one or two-story, word-frame building may have a duration of relatively constant magnitude, beginning about the time of (or shortly after) roof penetration and ending with general collapse; (see App. F) but it is usual for one portion of such a building to become heavily involved in fire before some other portion has experienced much fire. Accordingly, the emissive power with time can vary significantly at different points around the building. Clearly, any description of the radiation from a building based on temporally and spatially invariant properties can be seriously in error. If radiation heat transfer plays an important role in urban fire spread, and there is every indication that it does, some allowance should be made for intrastructural fire spread and structural fire behavior. Lacking anything more than a broad, stochastic description of target subareas, radiating characteristics of structures by structural class (taking into account the probable locations of initial fires) would have to suffice.

According to the Stefan-Boltzmann law, the radiant emittance (total radiant power emitted from each unit area) of a gray body is given by the equation $H_S = \epsilon \sigma T^4$, wherein ϵ is the emissivity (unity for a black body), σ is the Stefan-Boltzmann constant (1.356×10^{-12} cal cm^{-2} sec^{-1} deg^{-4}), and T is the absolute temperature of the emitter. Flame temperatures are typically 1000 to 1400°C. Glowing solid fuels usually are not as hot as flames, but their high emissivities cause them to have high radiant emittance. Flames are somewhat diathermanous to their own radiation. Their emissivities therefore are a function of their thickness. Emissivities in the order of 0.1 are to be expected for thin, well-ventilated flames, but optically thick flames (large dimensions of the flame perpendicular to the radiating surface and/or sooty flames) and flames that fill an enclosure can be expected to have nearly black-body emissive powers. Variations in emissive power with both temperature and emissivity are displayed in Table 1. An increase of 200°C in a flame temperature of 1000°C can approximately double the radiant emittance.

TABLE 1

Variations in Emissive Power With Temperature and Emissivity ($cal\ cm^{-2} sec^{-1}$)

T	ϵ = 1	.5	.2	.1	.05
1073°K(800°C)	1.8	0.9	0.36	0.18	0.09
1273°K(1000°C)	3.6	1.8	0.72	0.36	0.18
1473°K(1200°C)	6.4	3.2	1.3	0.64	0.32
1673°K(1400°C)	10.6	5.3	2.1	1.1	0.53

8.3.3 Convection Heat Transfer From Burning Buildings

The upward flow of the flames and hot gases from a burning fuel array, such as a building, is governed by (1) buoyancy resulting from the difference in density of the combustion gases and the surrounding air (which in turn is due, primarily, to the difference in temperature), (2) drag and viscous forces resulting from the motion of the combustion gases through the air, and (3) mixing, entraining, and cooling processes that cause the convection column to expand and its buoyancy to be reduced as it rises. Initially, the upward motion is one of acceleration as the buoyant force dominates, but the drag forces, which increase with speed, and the loss of buoyancy from cooling and mixing quickly dampen the upward acceleration, and a relatively constant speed (in tens of feet per second) results. Thus, a modest prevailing wind speed (say, 10 to 20 mph) can give a significant tilt to the convection column; that is, can cause it to move about as much horizontally as vertically. Thus, where building separations are not substantially greater than building heights, direct convective heat transfer in the downwind direction is a conceivable factor in fire spread.

The coalescence of convection columns is a factor in fire activity and spread. It appears that fully coalescent fires may burn at least twice as fast as fully independent fires. The increased heat-release rate added to the induced air motion on the ground in the vicinity of the fire would be expected to significantly increase the likelihood

(and rate?) of fire spread. The concerted interaction of large, spatially concentrated fires and its dependence on the structure of the atmosphere is logically a subject for the final section (Mass Fires, Sec. 9).

8.3.4 Fire Spread by Firebrands From Burning Buildings

The production, transport and fire-spread potential of brands cannot be analytically described or assessed at the present time (see Apps. D and F). The role of brands in past fires has been established, and they must be considered to be the primary agent for fire spread over large distances. In the absence of firefighting, no firebreak short of a desert or a major body of water can be considered to be completely reliable because of the possibility of spotting by brands.

Some of the parameters thought to be important are structural features and materials of the burning building (which will influence the number and sizes of brands produced), firebrand transport by convection and wind, and lifetimes of brands. The importance of these and other parameters in firebrand-propagating mechanisms will be known only after research of the subject.

The term firebrands is usually limited to burning solid objects that are lifted by the convection column and/or carried by the wind, but we mention here other burning fuels that are translated primarily by gravity. In areas of considerable slope, burning fuels (both liquid and solid) can be carried downhill from a fire into unignited fuels. This occurrence does not appear to be a very common one, but it must be considered in hilly areas. Even on flat ground, burning fuels may be translated distances comparable to building heights when burning buildings collapse. This mechanism is probably not too important in most cases because of its short range relative to other mechanisms, but it should not be ignored completely.

8.3.5 Fire Spread Through Exterior Fuels

A satisfactory, mechanistic model of fire spread through exterior fuels is not yet available despite the efforts that have been given to devising one (see App. F). As things stand now, no new factors can be added to the list of parameters previously derived from fire experience (8.2).

8.3.6 Initiation of Fire in Other Buildings

Up to this point, we have limited our attention to that part of the mechanics of fire spread concerned with the source, namely, the burning building or other burning fuels. We have noted that a discrete fire can be a source of radiated and convected heat, of convection-and wind-transported firebrands, and of other burning fuels translated by

gravity, and that a fire may propagate through continuous fuels adjacent to unignited structures proximate to burning buildings, and by the exposure of unignited fuels to radiant heat generated by burning fuels. The case of fire initiation in structures from proximate exterior fuels has been treated in Section 7 and is not considered further here.

Since fire experience has shown that the exterior walls of a burning structure collapse out to a distance somewhat less than the building height, unignited structures not in contact (before possible collapse) with burning structures can be set afire by burning debris (and in some limited cases, by liquid fuels) if they are within a distance equivalent to the building height of a burning structure or at somewhat greater distances if they are located downhill. Within roughly the same distances, direct convective heating would occur downwind with a moderate to strong local wind blowing. On steep slopes, buildings uphill from the source would be more apt to be heated convectively because of their higher elevation.

The radiant heat received by a building adjacent to one or more burning buildings is a function of the radiant emittance of the burning buildings and the parts of the unignited fuels' fields of view that are filled with radiant sources. As indicated previously (Section 8.3.2), the radiant emittance of flames and burning surfaces (per unit area) is about a fraction of a cal per sec to a few cal per sec (typically 1 to 3 and probably never more than 5 or 6). Since the irradiance at a receiver is equal to the emittance of the source times a view configuration factor,* this configuration factor must exceed 1/10 to 1/2 if irradiances are to exceed the ignition threshold levels of fuels, namely, a few tenths to about 1 cal $cm^{-2}sec^{-1}$. Configuration factors depend on the dimensions of the source(s) and the distance between the source and the fuel, the angle formed by the planes of the source and the fuel, and any obscuring objects or media.

Consider the case of an unignited fuel facing a nearly continuous row of burning buildings of roughly equal height that are radiating as though half the area of the row facing the receiver were a black body at 1000°C. To optimize the radiation transfer, ignore any possible obscuration and treat the row of buildings as an infinitely long strip source of height h. Also consider the surfaces of the fuel to be parallel to the strip and located h/2 above its base. For this case, the irradiance falling on the exposed fuel would be about 0.8 cal $cm^{-2}sec^{-1}$ at a distance equal to h and 0.46 cal $cm^{-2}sec^{-1}$ at 2 h. At the higher value, spontaneous ignition is marginally possible; at the lower value, piloted ignition must be present if ignitions occur. Thus, fire spread is likely when

* Ratio of actual irradiance to that which can be received from a source filling the entire field of view.

buildings are separated by distances comparable to building heights unless there is a wind strong enough to carry flames, sparks, or firebrands from the fire zone to radiantly heated (unignited) fuels; in which case, the fire may jump about twice as far. Piloted ignition probably would not occur at a distance as large as two building heights except for conditions of very high wind speeds, and rarely then is it likely that flames or other suitably hot substances would be carried (or would survive) a distance of two building heights or more to serve as a pilot.

It must be admitted that irradiance levels sufficient to cause spontaneous ignition could occur as much as four building heights away from a very long row of closely spaced buildings if they were radiating as a 1200°C black body of area equal to the total area represented by the row. A situation like this is quite unlikely and there are so many factors that tend to reduce the amount of received radiation that it appears much more likely that the distances of fire jumps by radiation alone will be closer to one building height than they will be to several building heights (see Table 2).

Thus far, we have only addressed our attention to radiant-exposure from burning buildings in relation to ignition thresholds of exposed fuels without regard to the consideration of how many fuels (of which kinds and in what locations) will be in a position both to receive a substantial part of the free-field irradiance and, if ignited, to propagate the fire to the structure with which they are associated. The structural details (type of construction, number of windows, arrangement of rooms of various occupancies, etc.), the orientation relative to burning fuels, and the nature of proximate exterior fuels will be the main determinants of the response of a structure to radiant heating. In the absence of highly combustible exteriors, the fields of view of interior fuels will determine whether a fire jump will occur. All of these factors have received attention in earlier sections of this report. To analyze fire spread by way of a radiant-heating mechanism, all of the foregoing parameters will have to be considered in detail for each situation.

For building separations greater than a few building heights (in the absence of heavy, nearly continuous distribution of exterior fuels between buildings), the only plausible mechanism for fire spread is by way of firebrands. Intuitively, we expect that firebrands carried by convection and wind to considerable distances from their origin will cause fires in structures primarily by way of roofs and other near-horizontal, combustible surfaces that are parts of the structures. The response of a structure will therefore (if our expectation is close to fact) be determined by the combustibility of roofs and similar surfaces and such factors as roof penetrability, fuel continuity to structural interiors, and the other factors of construction and weather that apply to propagation of primary fires to structures with combustible exteriors (see 6.2).

TABLE 2

Range of Ignition by Radiative Transfer as a Function of Building Height and Width

Temp. (^{o}C)	H_S (cal cm^{-2}sec^{-1})	H_R (cal cm^{-2}sec^{-1})	Φ	A_W/A_T	D/h* w = ∞	D/h* w = h
1000	3.6	0.8	0.222	1/2	1	0.6
1200	6.4	0.8	0.125	1/2	2	1
1200	6.4	0.8	0.125	1	4	1.5

* Values of D/h interpolated from Table F.3 (as modified for different window openings).

Definition of Terms:

H_S - Radiant Emittance of Source

H_R - Irradiance of Receiver

Φ - Configuration Factor = H_R/H_S

A_W, A_T - Source Window Area, Total Area

w,h - Source Width, Height

D - Separation of Receiver and Source

8.3.7 Rate of Spread and the Destruction of Specific Structures

Up to this point, we have been attempting in our considerations of the mechanisms of fire spread to enumerate the parameters that influence whether or not fire will spread to structures not initially set on fire by combined weapon effects, panic, non-attendance, etc., without regard to the temporal sequence of events. Obviously, our judgment of which structures will succumb to destruction by fire can be quite wrong, in some circumstances at least, if we ignore rates of progress; for clearly, the fire response of fuels is governed by the sum total of intensity of fire activity of adjacent (and in some cases remote) fuels at any given moment. This time-intensity pattern is a complex function of the time-sequence of fire behavior in the locale. Moreover, a fire assessment that fails to provide a picture of the fire situation with time is of little value since the whole question of mass-fire development depends on growth and termination, and most of the operational problems such as evacuation, rescue, firefighting, and pre-attack decisions (such as the location of shelters, etc.) require a knowledge of where the fires are with time and the rates and directions they are moving.

Fire will spread through heavily vegetated areas or other continuous fuel distributions at a rate determined by the mechanics of spread through continuous fuels (see App. F). No satisfactory mechanistic model is available. No new parameters can be enumerated.

For discrete fuel concentrations, such as structures, two cases can be considered: (1) When structures are close enough together (about a building height separation distance, for example) that jumps are deterministically certain, the rate of spread is governed primarily by the burning time of structures, or more specifically, the time between ignition of fuels on a side facing adjacent burning structures and full involvement of a side facing an unignited building. Burning time, in turn, is determined by a variety of structural parameters that cannot be mechanistically evaluated at the present time. Spread by firebrands will also cause new fires at random times and location. (2) When buildings are farther apart--beyond the reach of radiation and convection heating--the rate of spread will depend on the mechanics of firebrand transport and fire initiation by brands, neither of which is presently known well enough to analyze.

8.3.8 Reliability of Estimates and Ranking of Parameters

In approximate order of sensitivity the parameters affecting the rate, direction and extent of fire-spread are: (1) target/fuel parameters, (2) weather parameters, (3) topographic, and (4) other parameters. Each of these is subcategorized as follows:

1a. Fuel Parameters (Composition, physical properties [density, size, continuity, state of subdivision, thickness], moisture content, age, ignitability, burning time, heat release, translatability by wind, buoyant forces, etc.) 1b. Target Parameters (fuel load [concentration per unit volume and area], density of buildings [ground covered by buildings and separation distances], number and size of openings, number and size of enclosures). 2. Weather Parameters (wind speed and direction, humidity, air temperature, precipitation, insolation). 3. Topographic Parameters (slope, aspect, and elevation). 4. Other Parameters (number of openings emitting radiation, number of significant fires, geometry or shape of fires [line or area and shape of flames], location of fires in urban area and relative to each other.

SECTION 9

MASS FIRES

9.1 GENERAL

Up to this point, we have been concerned mainly with fire growth and behavior on a relatively small or local scale, treating the sequence of events in a single fuel array, enclosure, structure, group of structures, and relatively limited locale, as though they were quite independent of similar events that might be going on elsewhere. Such independence is usually the case in typical peacetime fires of limited scale and in fact is generally true during the early stages of fire development regardless of the magnitude of the incipient fire. But there is considerable evidence from the massive urban incendiary experiences of World War II, as well as from scattered cases of large-scale peacetime fires in both cities and forests, that new phenomena accompany fully developed fires of large magnitude, which suggest a strong, concerted interaction of the individual fires. Fires of this magnitude have been termed mass fires. They appear to fall into two categories: (1) fires that spread generally along a front, usually in the direction of the natural wind; such fires are called conflagrations, and (2) fires that burn with great intensity without spreading outside of the area initially involved and generate a strong vertical convection column that induces high winds near the ground; such fires are called firestorms. Both types of mass fires are characterized by strong convective interaction (called coalescence). Because of this, we expect that they depend on a highly concentrated pattern of heat release and perhaps in some way on the area involved.

9.2 CONFLAGRATIONS

Conflagrations are large propagating fires that have the capability of destroying (or severely damaging) areas much larger than the area of initial ignition. The conflagration is characterized by a fire front moving primarily in the direction of the natural wind. Based upon observations* of fire fronts there is some reason for believing that with sufficient convective activity--an implied requirement of any mass fire--a large fire front may generate its own wind that will cause it to propagate at a rate significantly greater than would a smaller fire, all other factors being equal. Aside from this possible convective enhancement of rate of spread, there is really nothing basically new

* Craig C. Chandler, U.S. Forest Service, private communication.

about the conflagration-type mass fire, and the parameters that govern its behavior are the same as those discussed at length in the preceding section. The convective behavior of mass fires is not at all well understood and a suitable model of a conflagration has yet to be devised.

Whether or not a conflagration will occur seems to depend on a number of factors having to do with the pattern and concentration of initial fires, the nature and concentration of fuel into which they might propagate, and characteristics of the atmosphere, most notably, the wind speed near the ground. The direction and rate of spread of the conflagration will depend on much the same factors, but of course, its behavior will become less dependent on the nature of the initial fire as time progresses.

Building density should be mentioned as a major determinant of whether a conflagration (or any mass fire) will occur. Experience indicates that, unless building density exceeds some level (perhaps 20%), mass fires will not occur. Appendix F discusses in detail the dependence of fire behavior on building density. One point that should be emphasized here is that in a spreading fire, by no means all of the buildings in an area through which the fire spreads will be destroyed. For total destruction the building density probably would have to be extremely high. Building density (or some other measure of fuel concentration and type) and wind speed and direction are probably the main determinants of the rate and direction of progress of a conflagration.

9.3 FIRESTORMS

Historically, the term firestorm was first applied to fires having all of the usual characteristics of a storm: gale winds, clouds, and rain. At Hamburg, the best-known example and probably the first urban firestorm in history, all of these characteristics were reported by observers. The clouds and precipitation may be features of a massive-fire convection column, but they are certainly of secondary importance to the subject of urban fire vulnerability. The wind, on the other hand, is a major factor and remains as a common element of all more recent attempts to define a firestorm. Current definitions (or descriptions) are basically modifications of the following: A firestorm is a mass fire that does not spread appreciably outside of the area initially involved (at least not during the firestorm phase), but burns with great intensity, creating strong, vertical convective activity and inducing strong indrafts near the ground.

The requirements for a firestorm seem to be much the same as those for any mass fire (high fuel density, a large area burning at one time, etc.), but in addition there appear to be some special atmospheric parameters involved. The strong, vertical convective formation, which appears to be a characteristic of firestorms, would be enhanced by an

unstable atmospheric lapse rate and low initial wind speeds particularly near the ground. The dimensions of the fire area should be large compared to the thickness of the atmosphere but this tends to retard the development of the convection column. There is also some evidence of a requirement for ambient wind shear (horizontal gradient in wind speed) to provide the high surface winds through conservation of angular momentum in the air drawn into the base of the convection column. Thus, it might be reasonable to postulate the following requirements for the formation of a firestorm: near simultaneous development of fires in at least half of the structures in an area about a square mile or more in which the building density is at least 20%, where the surface wind is only a few miles per hour (with shear perhaps), and the atmosphere over the urban area has an unstable lapse rate. The last requirement may not be of great importance (or of importance only for marginal circumstances) because of the magnitude of buoyant forces and dimensions of the zone of convective activity that may dominate the atmospheric structure. Besides that, it is quite likely that in many circumstances the fireball of a large weapon could effectively "punch a hole" through an inversion layer and set up a virtual "chimney" of fluid-dynamic structure over the target that would override unfavorable ambient conditions of the atmosphere.

9.4 RANKING OF MASS-FIRE PARAMETERS

In approximate order of sensitivity, the parameters affecting mass-fire development are: (1) fuel concentration, (2) size of initial fire area, (3) initial fire density, (4) fuel type, (5) surface wind (6) distribution (configuration of burning area) of initial fire, (7) atmospheric structure, and (8) topography. The first several of these determine whether a mass fire will occur and influence its magnitude and severity, and the last (particularly the last four) determine whether it will behave as a conflagration or a firestorm.

9.5 PRESENT INFORMATION DEFICIENCIES

Since the fire vulnerability of urban areas is strongly dependent upon transmission of thermal radiation through the atmosphere and because there are little reliable data for transmission through clouded and hazy atmospheres, further research efforts should be made in this area. In addition, major information gaps exist in sensitive areas such as the detailed description of fuels (especially the fields of view or location of fuels), the mechanics of the development of significant fires from primary ignitions, the mechanics of fire growth in enclosures, the mechanics of firespread (particularly firebrand propagation), and the fire behavior of large-scale convective columns and coalescence of fires. At the present it is possible to assess incendiary vulnerability only via intuitive-stochastic approaches based on fire experience, and this approach is of doubtful reliability for civil defense purposes.

SECTION 10

CONCLUSIONS AND RECOMMENDATIONS

The most useful conclusion to this report would be a single list of parameters in decreasing order of importance to urban fire vulnerability. However, such a list would be quite arbitrary and at the current level of knowledge would produce a result without real value. To clarify this point, we will enumerate the reasons why such a list cannot be provided:

1. The choice of parameters depends upon the method of analysis.

2. Some aspects of the problem are not sufficiently well understood to permit sensitivity analysis.

3. Entirely different sets of parameters may dominate under very different conditions.

The first two points have been adequately treated in earlier portions of this report, but perhaps the last point requires additional clarification.

Under some conditions of attack, the fire vulnerability of an urban target, as gauged by the anticipated final extent of incendiary damage, may bear little or no resemblance to the area initially affected by the thermal radiation emitted by the nuclear fireball. This could be the case when there are weather conditions which strongly attenuate the thermal radiation or in a highly urbanized (or "thermally hardened") area where kindling weight fuels may be sparse. Fires caused by blast, non-attendance, and other non-thermal radiation causes could dominate the fire picture and the important parameters would be those related to the production of secondary and tertiary fires. At the other extreme, when the weather and fuel factors are right for it, fires may spread to destroy an area many times larger than that initially ignited, in which case the dominant parameters would be those which govern fire spread. In these examples, the extreme conditions of weather and fuel not only affect the fire outcome in the manner of a sensitive parameter; they also bring about a gross change in character of the fire from that of the more usual range of values of these variables and accordingly an extensive reordering of the sensitivity of the result to all parameters. We will refer to the extreme value ranges of such variables as <u>constraints</u> on the system.

If we eliminate from consideration, for the time being, all such extreme cases as the examples above, we are left with the cases where the final fire outcome is in large measure determined by the magnitude of the primary fire. The consensus of opinion of many "fire experts" is that this situation will apply to the large majority of cases.* Since the vulnerability is strongly influenced by the magnitude of the primary incendiary response of the urban area, the sensitivity order of parameters will be determined largely by the factors that govern the distribution of thermal radiation, the response and ignition of kindling fuels, and the growth of significant fires from ignited kindling.

Thus, we are able to break the task down into parts governed by the following lists of parameters. The parameters are cited in approximately decreasing order of importance; the comparison of the relative importance of any two parameters on the same list will be more valid if the parameters are widely separated on the list. In the first list (distribution of primary fires) those parameters that are considered to be of key importance are separated by a line from the less important parameters. Parameters which are significantly sensitive to time (prior to burst) are labeled (D) if the parameter is most sensitive to the time of day, (W) if the parameter is most sensitive to the day of the week, and (S) if the parameter is most sensitive to the season of the year.

* In other words the number of buildings ultimately destroyed by the fire typically will be approximately equal to the number which are initially involved; or at most the area burned over will not be significantly larger than that enclosed by the primary fire perimeter. In practice, one of the problems in vulnerability analysis would be the evaluation of constraints that separate typical cases from those which might result in firestorms or conflagrations.

I. Parameters Governing the Initial Distribution of Significant Fires Caused by Thermal Radiation Only

IA. Limited Thermal Shielding	IB. Extensive Thermal Shielding
1. Burst Location Relative to "Homogeneous" Urban Subarea.	1. Burst Location Relative to "Homogeneous" Urban Subarea.
2. Weapon Yield.	2. Height of Burst(Above Surface).
3. Height of Burst (Above Surface)	3. Weapon Yield.
4. Transmission of Haze-Cloud Layers Below Burst Point. (D)	4. Location of Kindling Fuels Relative to Windows and Walls.(S)
5. Kindling Fuel Load. (S)	5. Location, Area, and Number of Windows.
6. Weight Per Unit Area* of Fuels in Target. (S)	6. Thermal Transmission of Window Coverings; Shielding of Interior Fuels. (D)
7. Location of "Thin" Fuels with Regard to "Thick" Fuels. (S)	7. Ratio of Heights of Structures to Separation Between Structures.
8. Albedo of Cloud Layer(s) Above Burst Point. (D)	8. Transmission of Haze-Cloud Layers Below Burst Point. (D)
9. Target Surface Albedo. (S)	9. Scattering Properties of Atmosphere (Angular Distribution).(D)
10. Burst Altitude (Above Sea Level); Atmospheric Density.	10. Weight Per Unit Area of Fuels in Target. (S)
11. Absorptance of Fuels**	11. Location of "Thin" Fuels with Respect to "Thick" Fuels. (S)
12. Local Relative Humidity***	12. Albedo of Cloud Layer(s) Above Burst Point. (D)
13. Composition of Kindling "Thin" Fuels	

* Fuel thickness itself is a parameter, but a much less important one; for this reason the thickness of fuels will be expressed in weight per unit area.
** Depends upon the spectral distribution of thermal radiation and the spectral absorptance of fuels, neither of which is typically subject to large variation.
*** Not subject to large variation for interior fuels; ignition of exterior fuels is sensitive to precipitation (D).

IA. (Cont.)	IB. (Cont.)
14. Kindling Fuel Geometry (Long Pulses Only*)	13. Albedo of Target Surface.(S)
15. Fuel Burning Rates (Surface/Volume Ratio, Combustibility (S), Air Motion (D), Fuel Configuration, Ventilation (D), Moisture Content (D), Proximity of Other Burning Fuels and of Unignited Objects and Surfaces (S)).	14. Albedos of Walls and Other Reflecting Surfaces.(S)
	15. Thermal Shielding by Foliage.(S)
	16. Location and Height of Topography Relative to Kindling Fuels. (S)
16. Relative Radiative and Convective Heat Fluxes.	17. Burst Altitude (Above Sea Level); Atmospheric Density.
17. Dimensions and Structural Features of Enclosures (Including Sources of Ventilation (S)).	18. Absorptance of Fuels**
	19. Local Relative Humidity*** (D)
	20. Composition of Kindling ("Thin") Fuels.
18. Building Density (Separations, Plan Areas, Heights).	21. Kindling Fuel Geometry (Long Pulses Only).
19. Building Construction (Type, Use, Exterior Covering).	22. Fuel Burning Rates (Surface/Volume Ratio, Combustibility (S), Air Motion (D), Fuel Configuration, Ventilation (D), Moisture Content (S), Proximity of Other Burning Fuels and of Unignited Objects and Surfaces)
20. Surface Wind Speed and Direction.(D)	
21. Thermal Shielding by Foliage.(S)	
22. Shielding of Interior Fuels by Window Coverings.(D)	23. Relative Radiative and Convective Heat Fluxes.
23. Spectral Absorptance of Atmosphere.(D)	24. Dimensions and Structural Features of Enclosures (Including Sources of Ventilation (D)).

* Bursts of large yield at low altitude.
** See footnote on page 75.
*** See footnote on page 75.

IA. (Cont.)	IB. (Cont.)
24. Weapon and Vehicle Design.	25. Building Density (Separations, Plan Areas, Heights)
	26. Building Construction (Type, Use, Exterior Covering).
	27. Surface Wind Speed and Direction. (D)
	28. Spectral Absorptance of Atmosphere. (D)
	29. Weapon and Vehicle Design.

II. Parameters Governing the Initial Distribution of Significant Fires Resulting from Blast and Other Causes

IIA. Low Altitude Bursts (Significant Blast Damage on the Ground)	IIB. High Altitude Bursts* (Little or no Thermal or Blast Damage on the Ground)
1. Weapon Yield.	1. Warning Time prior to Burst.(S)
2. Height of Burst (Above Surface)	2. Number of Persons not Alerted to Attack.
3. Burst Location Relative to "Homogeneous" Urban Subarea.	3. Preparation and Training of Population.
4. Ignitable Fuel Load. (S)	4. Distribution and Activities of Population. (W)
5. Number and Location of Potential Ignition Sources.(S)	5. Number of Potential Tertiary Fire Hazards. (W)
6. Construction Type of Structure.	6. Proximity of Potential Tertiary Fire Hazards to Other Fuels. (W)
7. Susceptibility of Pipes, Conduits, Containers, etc., to Blast Damage.	7. Yield of Burst.
8. Proximity of Combustible Fuels Relative to Potential Ignition Sources. (D)	8. Slant Range to Observer.
9. Proximity of Ignitable Fuels Relative to Other Fuels. (S)	9. Atmospheric Transmission. (D)
10. Total Fuel Load. (S)	10. Height of Burst (Above Surface).
11. Energy Use in Urban Subarea.(D)	
12. Ambient Condition of Fuels.(S)	
13. Distribution of Fuels. (S)	
14. Topography (As the slope either attenuates or strengthens the blast wave.)	
15. Safety Mechanisms on Utilities and Industrial Equipment.	
16. Altitude of the Urban Area (As it influences blast overpressure levels.)	

* or far distant, or false alarm.

III. Parameters Governing Spread of Fire (Conventional Magnitude) and the Resulting Destruction of Resources

IIIA. Structure to Structure Spread	IIIB. Spread Through Exterior Fuels to Structures
1. Construction Features of Structures (Number, Size, and Location of Outer-Wall Openings; Combustibility of External Coverings (S); Roof Type, Building Dimensions, and Shielding of Interior Fuels by Window Coverings.(S)	1. Proximity of Exterior Fuels Relative to Structures. (S)
2. Builtupness of Urban Subarea (As Determined by Building Density, Height of Structures, and Separation Distances between Structures).	2. Exterior Fuel Load and Type (Trash Accumulation, Fuel Storage, or Vegetation). (S)
3. Fuel Type (Composition, Density, Size, Thickness, Subdivision, Age, and Other Parameters which Govern Ignitability, Burning Time and Heat Concentration).	3. Width and Configurations of Firebreaks.
4. Building Fuel Load. (S)	4. Builtupness of Urban Subarea.
5. Configuration and Intensity of Initial Fire-Involved Structures.	5. Structural Features (As They Govern the Susceptibility of Structures to Ignition): Structural Condition After Primary Blast and Thermal Effects; Number, Size, and Location of Openings. (D) Construction Type, Exterior Coverings, Fire Susceptible Structural Features, Geometry (Thickness and Surface Area), and Fuel Load.
6. Moisture Content of Fuels.(D) (As Determined by Relative Humidity, Precipitation and Air Temperature.)	6. Firebrand Characteristics of Burning Exterior Fuels (Sparking, Firebrand Production, Hot Gas Formation).
7. Wind Speed and Direction Relative to Direction of Spread. (D)	7. Relative Humidity and Precipitation. (D) (As They Govern the Rate of Spread and Burning Intensity of Exterior Fuels.)
8. Number, Geometry, Weight and "Life-times" of Firebrands.	8. Proximity of Sustained Exterior Structural Ignitions Relative to Openings.
	9. Wind Speed and Direction Relative to Fire-Susceptible Structures. (D)

IIIA. (Cont.)	IIIB. (Cont.)
9. Emissivities and Shape of Flames Issuing from Openings [and from Roof if penetrated] and Glowing Solid Fuels.	10. Ambient Condition of Fuels. (S)
10. Susceptibility of Structural Features to Firebrands. (S)	11. Housekeeping (S) (As it Influences the Ignition Susceptibility of Structures, the Distribution of Fuels, and the Total Fuel Load).
11. Width and Configuration of Firebreaks.	12. Location of Exterior Sustained Burning on Structures.
12. Density Gradients, Drag and Viscous Forces of Gases Above Burning Structures. (As They Govern Buoyant Convection and Degree of Coalescence of Fires)	13. Snow Cover. (S)
	14. Shielding of Structural Features and Interior Fuels by Foliage. (S)
13. Snow Cover. (S)	15. Topography (Slope, Aspect, and Elevation).
14. Fuel Distribution. (S)	
15. Ambient Condition of Fuels. (S)	
16. Topography (Slope).	

IV. Parameters Governing the Destruction of Resources by Mass Fires

IVA. Conflagration	IVB. Firestorm
1. Construction Features of Structures (Number, Size and Location of Outer-Wall Room Openings; Combustibility of Exterior Coverings; Roof Type; Window Coverings (D)).	1. Builtupness of Urban Subarea (Building Density, Height of Structures, and Separation Distances Between Structures).
2. Number, Geometry, Weight and "Life-times" of Firebrands. (S)	2. Configuration and Intensity of Initial Fire-Involved Area.
3. Susceptibility of Structural Features to Firebrands. (S)	3. Fuel Type (Composition, Density, Size, Thickness, Subdivision, Age and Other Parameters which Govern Ignitability, Burning Time, and Heat Concentration).
4. Wind Speed and Direction Relative to the Direction of Spread. (D)	4. Building Fuel Load. (S)
5. Width and Configuration of Firebreaks.	5. Construction Features of Structures (Number, Size, and Location of Outer-Wall Room Openings (D); Combustibility of External Coverings (S); Roof Type; Window Covering (D)).
6. Configuration and Intensity of Initial Fire-Involved Area.	6. Atmospheric Structure (Lapse Rate, Horizontal Wind Shear, and Surface Wind Speed). (D)
7. Building Fuel Load. (S)	7. Width and Configuration of Firebreaks.
8. Fuel Distribution. (S)	8. Density Gradients, Drag and Viscous Forces of Gases Above Burning Structures (As They Govern Buoyant Convection and Degree of Coalescence).
9. Proximity of Exterior Fuels Relative to Structures. (S)	9. Emissivities and Shape of Flames Issuing From Openings (and from Roof if Penetrated) and Glowing Solid Fuels.
10. Moisture Content of Fuels (As Determined by Relative Humidity, Precipitation, and Air Temperature (S)).	10. Distribution of Fuels. (S)
11. Builtupness of Urban Subarea (Building Density, Height of Structures, and Separation Between Buildings).	
12. Emissivities and Shape of Flames Issuing from Openings (and from Roof if Penetrated) and Glowing Solid Fuels.	

IVA. (Cont.)	IVB. (Cont.)
13. Fuel Type (Composition, Density, Size, Thickness, Subdivision, Age and Other Parameters which Govern Ignitability, burning time, and Heat Concentration).	11. Topography (As it Governs Initial Fire-Involved Area).
14. Ambient Conditions of Fuels. (S)	12. Moisture Content of Fuels (As Governed by Relative Humidity, Precipitation, and Air Temperature (S)).
15. Density Gradients, Drag and Viscous Forces of Gases Above Burning Structures (As They Govern Buoyant Convection and Degree of Coalescence).	
16. Snow Cover. (S)	
17. Topography (Slope, Aspect, and Elevation).	

Using the foregoing lists of parameters we can enumerate (in approximate order of sensitivity) the parameters which govern the following 7 categories of urban fire response that include most (if not all) of the cases of interest:

Response Type 1 - Extent of Fire Vulnerability is Determined Primarily by the Extent and Number of Initial Fires Caused by Thermal Radiation.

Constraints: Conditions for spread less extreme and constraints for Response Types 2 and 3 are not satisfied.

Category A - Limited Thermal Shielding

Additional Constraints: Ratio of building separation to height much greater than 1, and no significant shielding by foliage or topography; many interior fuels near exposed windows (or many exterior fuels).

Ranking of Parameter Groups in Order of Importance: IA, IIIA, II, IIIB.

Category B - Extensive Thermal Shielding

Additional Constraints: Ratio of building separation to height ≤ 1 (or significant shielding by walls, foliage, window coverings, and topography), or "thermally hardened."

Ranking of Parameter Groups in Order of Importance: IB, IIIA, II, IIIB.

Response Type 2 - Extent of Fire Vulnerability is Determined Primarily by Spread or Ultimate Magnitude of Fire (Little Relationship Between Number of Structures Initially on Fire and the Number Ultimately Destroyed.)

Category A - Spreading Fire of Conventional Magnitude

Constraints: Conditions for spread very favorable and conditions for mass fires (Response Type 2, Category B. Conflagration and Category C. Firestorm) are not satisfied. High concentration and contiguity of fuels combined with structures having combustible exteriors and a hazardous fire weather condition.

Ranking of Parameter Groups in Order of Importance: IIIB, IA, IIIA, IIA.

Category B - Conflagration

Constraints: High fuel loading, brisk surface wind, large number of structures in fire area simultaneously on fire, large fire area.

Reasonable Estimates: Fuel loading $\geq$ 8 pounds combustibles/ft.^{2} of fire area, surface wind $\geq$ 8 miles/hr., initial fire density > 50% (% of structures in fire area simultaneously on fire), initial fire area > 0.5 mi.^{2}

Ranking of Parameter Groups in Order of Importance: IVA, III(A or B), IIA.

Category C - Firestorm

Constraints: High fuel loading, low initial surface wind, large number of structures in fire area simultaneously on fire, large fire area (roughly circular in shape).

Reasonable Estimates:* Fuel loading $\geq$ 8 pounds combustibles/ft.^{2} of fire area, initial fire density > 50% (% of structures in fire area simultaneously on fire), surface wind < 8 miles/hr., fire area > 0.5 mi.^{2}

Ranking of Parameter Groups in Order of Importance: I(A or B), IVB, IIIA, IIA, IIIB.

Response Type 3 - Extent of Fire Vulnerability is Determined Primarily by Fires Resulting from Blast or Other Causes

Category A - Blast-Caused Fires

Constraints: Atmospheric transmission, distance from ground zero, yield, and height of burst combinations such that thermal radiation levels are less than those necessary to ignite the most susceptible kindling fuels at distances where overpressure levels are sufficient to cause significant structural damage.

* Rodden, Robert M., John, Floyd I., Laurino, Richard, "Exploratory Analysis of Firestorms," SRI, Menlo Park, OCD Subtask 2536D, May, 1965.

Ranking of Parameter Groups in Order of Importance: IIB, I(A or B), IIA, III(A or B), IVA.

Category B - Panic - or False Alarm-Caused Fires

Constraints: Atmospheric transmission, distance from ground zero, yield, and height of burst combinations such that nowhere on the target are thermal radiation levels intense enough to ignite the most susceptible kindling fuels and additionally the overpressure levels are insufficient to cause significant structural damage.

Ranking of Parameter Groups in Order of Importance: IIB, I(A or B), IIA, III(A or B), IVA.

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APPENDIX A

TARGET PARAMETERS

A.1 GENERAL

A.1.1 Purposes of Appendix

The material in this appendix was chosen and is presented to:

1. Provide guidance to those who would conduct surveys of urban areas for the purpose of gathering input data for fire-assessment procedures.

2. Provide as complete a set of parameters as might be required in any fire-vulnerability models (or technique) based on approaches ranging from detailed (as practical) mechanistic approaches to broad-brush stochastic approaches.

A.1.2 Specific Objective

This appendix summarizes current thinking on how one might describe an urban area* (and its surroundings) in sufficient detail to allow assessment of the fire vulnerability of the area if it were the scene of one or more nuclear explosions of unspecified yield, location, and time. Specifically, we are searching for a set (or sets) of parameters that can be used in devising any model of an urban area (either generally or for each specific case) that will reasonably simulate the natural and manmade topography, manmade structures, vegetation, meteorology, combustible fuels, and other features of an urban area that are anticipated, or known, to be important.

A.1.3 Limitations of Detailed Description

Consideration of the various fire-defense countermeasures has been excluded from this appendix except where unavoidable; future reports should consider the full implications of such measures. This study has

*An urban area is defined as comprising either a city or a town as distinguished from country (rural) areas.

also been limited to those conditions considered to be likely at the present time and within about a decade. We believe that it is impractical to attempt a completely detailed analysis for two reasons: (1) lack of precise knowledge about such factors as atmospheric transmission, firespread rates, and the unpredictability of the weather, weapon yield, burst point, and burst time; and (2) the detailed description of the target will change continuously with time. Even if we were to send an army of data gatherers into a particular city and had available high-speed data-processing equipment of unlimited capacity to assimilate their findings, we would have a detailed description of that one city that would be applicable only for the time of the survey. Therefore, what is really needed is a more generally applicable description that averages wherever possible over the relatively homogeneous areas of a city and its surroundings, over the seasonal changes in the weather, over fuel distribution, and [illegible] larger metropolitan regions.

A.2 DIVISION OF URBAN AREA [illegible] SUBAREAS WITH EXAMPLE DESCRIPTION

A.2.1 Division Criter[illegible]

The large number [illegible] description of the fire vulnerability of [illegible] of the parameter values for that area [illegible] characteristics among different urban areas [illegible] methods that simplify the division and descri[illegible]. The division of an urban area into sub[illegible] for description of each structure and [illegible] can be described as having certain [illegible] parameter considered necessary for fire-vulnerab[illegible] area can be determined from spot surve[illegible] distribution value for each subarea, [illegible] compared with similar distributions [illegible] cities. We are interested in minimizing the [illegible] to make these generalizations.

Cities [illegible] according to several different criteri[illegible]. These divisions have been made [illegible] or fire zones in a city. The [illegible] of water, vacant areas, etc., (or low [illegible] zones were most often delineated by rows of [illegible] buildings on opposite sides of a particular [illegible].

The breakdown of a [illegible] be made on the basis of many other criteria, and [illegible] method of division depends on how sensitive each [illegible] fire parameters is to the description of each subarea. [illegible] other than those mentioned above,

for the division of an urban area into subareas are numerous; however, few have been previously investigated. Some of these are as follows:

Land use (human activity)
Occupancy of buildings
Density of structures
Fireload per unit area
Economic divisions
Population divisions
Political divisions
Ground cover
Vegetation cover
Insurance Rate Zones.

Fire experts have frequently used land-use criteria or classes to divide an urban area into subareas. A representative listing of such division by previous authors is as follows:

Sauer, Chandler, and Arnold[1]

Class 1. Residential:
Slum
Poor
Good

Class 2. Commercial:
Large manufacturing
Small manufacturing
Wholesale distribution
Downtown retail distribution
Neighborhood retail distribution
Waterfront

Bruce and Downs[2]

Good residential
Medium residential
Poor residential
Neighborhood retail
Downtown retail and office buildings
Wholesale and warehouse
Factory
Public buildings (schools and churches)
Waterfront
Parks and open areas.

Chandler, Storey, and Tangren[3]

Light residential

Heavy residential
Commercial
City center
Massive manufacturing

Civil Defense Urban Analysis (1953)*

Residential
Commercial
Industrial
Transportation
Storage
Institutional
Special
Recreational
Unused Land

These subareas are considered to be "homogeneous" if they may be described as having uniform properties with regard to fire vulnerability. Random spot surveys in each area are used to substantiate the frequency and value of each fire-vulnerability parameter. Some subareas will be found to be highly sensitive to certain fire-vulnerability parameters, whereas others will display a rather broad range of values.

A.2.2 Example Division of an Urban Area into "Homogeneous" Subareas by Land-Use Class for Transient Exterior Fuels

An example of urban-area description by land-use classes made by Sauer, Chandler, and Arnold[1] is given here. In their survey of transient exterior fuels (defined in A.5.1) they defined slum residential subareas as those containing single or multiple dwellings where 25% or more of the units or blocks are dilapidated.** These dwellings are generally of wood construction and closely spaced with little open yard area. Poor residential subareas contain single and multiple dwellings where between 2% and 25% of the units or blocks are dilapidated. These dwellings are generally of wood construction and surrounded by large but poorly tended yards. Good residential subareas contain less than 2% dilapidated units or blocks and include the newer residential tracts, the high-economic-income districts, and most apartment houses. Fire-retardant constructions prevail in these subareas, and the yard space is variable but well tended.

*Reference 4. These divisions are specified for fire in addition to other weapon effects important to OCD planning.

**The U.S. Census defines dilapidated as the state of a dwelling when it is so run-down or neglected, or is of inadequate original construction, that it does not provide adequate shelter or protection against the elements, or it endangers safety of the occupants.

Large-manufacturing subareas occupy 2 acres or more and produce or assemble goods. These are generally found adjacent to the main lines of transportation and are generally fire-resistant buildings surrounded by large open storage and yard spaces. Small-manufacturing subareas occupy less than 2 acres and also produce or assemble goods. These subareas are found scattered throughout the commercial areas of a city. The construction types of the buildings in these subareas vary widely, since the buildings were generally intended for different purposes. These subareas have a higher building density than large-manufacturing subareas, but have the lowest densities of any other commercial areas.

Wholesale-distribution subareas consist of those areas that are used for the handling and storage of goods intended for sale to retailers, and are concentrated near transportation terminals. Construction types in these subareas vary, but flimsy wooden or sheet-steel storage sheds predominate (in sample surveys by Sauer et al.[1]--Boston and Oakland). The downtown retail-distribution subareas are used for storage and display of goods intended for sale to customers and catering to buyers from the entire metropolitan area. These subareas are considered the "heart" of the city and are the subareas most likely to contain multistoried buildings; they are small in area and high in building density.

Neighborhood retail-distribution subareas are those areas used for the storage and display of goods intended for sale to consumers and catering primarily to buyers from the immediately adjacent residential areas. These areas are most commonly located along the most traveled streets of the residential subareas. Most often these consist of one-story buildings or the ground stories of multistory residential buildings. The building construction in these areas approximates the conditions in the surrounding neighborhoods.

Waterfront subareas are for the servicing of boats and ships. Fireloads are high but are generally well tended.

Any of the above subareas, or any subareas defined by other classifications, may be said to be homogeneous when they can be described by many similar or preferably identical values for any defined fire-vulnerability parameters. Any fire parameter occurs in any given subarea according to a distribution curve, which may be determined from spot or detailed surveys. A "homogeneous" subarea is one in which the value of the fire parameters that define the subarea may be described as being statistically constant. A comparison of these constants for other similar subareas in the same city or in other cities will reveal the extent to which these subareas may be considered to be homogeneous.

A.3 IDENTIFICATION AND DETERMINATION OF PARAMETERS REQUIRED TO DESCRIBE URBAN-AREA PHYSICAL FEATURES

A.3.1 Gross and Detailed Parameters

In preparing descriptions of urban areas that are to be useful for both overall fire assessment and detailed room-to-room fire spread, it soon becomes apparent that the areas being described vary in size from an area around a single fuel element at a specific location to a very large geographic region around an urban area containing a wide variety of different fuel elements. Since the size of the area to be described reflects the complexity of the description required (or possible), it is prudent to indicate the size of the area under consideration because size will determine for the most part the degree and methods of description. The parameters required to physically describe an urban area, which we will identify and discuss with regard to how the parameters may be obtained, may be broadly grouped into gross and detailed parameters.

Such grouping appears to be justified if we examine the various sources of urban data and the methods by which the data can be obtained. In some cases, however, the distinction between gross and detailed parameters is not clear-cut. For our purposes, we will consider gross parameters as (1) those parameters that are generally applicable to any urban area, in contrast to those detailed parameters that are applicable to only a specific urban area and (2) those parameters that are obtainable from aerial photographs, small-scale maps and other gross methods for surveying large areas, in contrast to those detailed parameters obtainable from room-to-room inspection and Sanborn maps (large scale).

A.3.2 Categories of Urban-Area Physical Features

The physical features (whether described by gross and/or detailed parameters) of any urban-area target necessary to a description of its fire vulnerability may be grouped into the following categories:

A. Ground Surface Features and Water Areas (topography, unstructured and unvegetated land, and water areas)

B. Structures

C. Vegetation

D. Meteorology

E. Fuels (Type, Distribution, Fields of View, Ambient Conditions)

A summary identification of the physical features in these categories is given in Table A.1. Let us now examine each of these categories with the purpose of identifying the parameters involved and for determining the methods by which they may be obtained and expressed.

TABLE A.1

Summary Identification of Physical Factors Affecting Urban-Area Fire Vulnerability

	Examples
A. <u>Ground-Surface Features and Water Areas</u>	
1. Ground-surface features	
a. Topography of region of city or town	mountains valleys plains
b. Topography of urban area	hilly flat
2. Water areas	
a. Large adjacent water areas	oceans lakes (large) bays
b. Water areas within urban area	ponds, ditches, canals, small lakes
B. <u>Structures</u>	
1. Enclosed fixed-location structures	
a. High fuel value	
(1) Buildings (walls and a roof)	houses, factories schools, hospitals, stores, offices
(2) Others	fuel storage tanks (liquid and gas); wooden storage crates

b. Low fuel value	
(1) Nonfuel tanks	water tanks, compressed air tanks, liquified gaseous nonfuels (like liquified nitrogen)
(2) Empty nonfuel or fuel tanks or nonfuel containers	empty gasoline refinery tanks, empty water tower tanks
2. Enclosed transient-location structures	
a. High fuel value	vehicles of transportation: automobiles, trolleys, trucks, airplanes, railroad cars, buses, ships at dock (or near harbor); small cardboard or paper containers
b. Low fuel value	empty railroad tank cars, electric vehicles
3. Open fixed-location structures	
a. High fuel value	wooden automobile and railroad bridges, utility poles; grandstands in certain places of assembly; billboards; wooden fences; coal yard piles; lumber yard piles
b. Low fuel value	freeways, roads, streets, sidewalks (considered part of street), airport runways, driveways, railroad tracks, concrete lined ditches, paved parking lots,

b. Low fuel value (Cont.) — concrete and/or steel bridges; piles of dirt, sand, salt, etc.; steel fences, certain steel (roofless) towers and structures

4. Open transient-location structures

   a. High fuel value — litter: newspaper, plastic and paper wrappers; cotton bales; saw dust piles

   b. Low fuel value — aluminum foil litter

C. Vegetation

1. Heavy vegetative fuels (fixed, open)

   a. Conifer trees - standing

   b. Deciduous trees - standing

   c. Large limbs - fallen

   d. Others

2. Medium vegetative fuels (fixed, open)

   a. Brush - standing

   b. Medium-sized sticks and branches

   c. Others

3. Light vegetative fuels (fixed or transient*, open)

   a. Needles

   b. Leaves

   c. Grass

   d. Others

*See footnote p. 103

D. Meteorology (as a Target Parameter)
(local and area-wide, interior and exterior)

1. Atmospheric pressure (regional)

a. Highs } for prediction of gross weather patterns.
b. Lows

2. Temperature and Relative Humidity

a. Interior

(1) Natural ventilation

(2) Heating and cooling systems

b. Exterior

3. Winds

a. Speed

b. Direction

4. Precipitation and Ground Fog

a. Rain

b. Snow

c. Ground fog

E. Description of Fuels

1. Type -- classified according to the following:

a. Physical state

b. Chemical composition

c. Use

d. Geometry (dimensions)

e. Treatment

f. Others

2. Distribution

   a. Fixed and transient (change in location with time)

   b. Exterior and interior (location with respect to and within enclosure)

3. Fields of view

   a. Fuels in the open
   b. Fuels in enclosures
   } anisotropic patterns

4. Ambient Conditions (local)

   a. Interior

      (1) Ventilation (sizes of opening) } micro wind speed and direction

      (2) Heating systems
      (3) Cooling systems
      } temperature and relative humidity

      (4) Location in enclosure with respect to opening

   b. Exterior

A.4 GROUND-SURFACE FEATURES AND WATER AREAS

A.4.1 Ground Surface Features (Topography)

It should be noted in Table A.1 that those structures designated with low fuel values usually have very low or no fuel value, whereas those designated with high fuel value have quite a broad spectrum of fuel values. Those structures classed according to high or low fuel value refer to structures within each class and are not to be a comparison of all structures according to fuel values. A physical description of urban topography (see Table A.1) of sufficient accuracy for our purposes may be readily determined from topographic maps and/or aerial photography. The status of topography in the U.S. may be obtained from either the National Atlas of the U.S. or from the U.S. Geological Survey (Washington 25, D.C.). The scale of current maps of the U.S. Geological Survey is usually $\frac{1}{24000}$, or $\frac{1}{31680}$ (2" = 1 mile). The Survey publishes an index map for each state that outlines the areas covered by, and the availability of, topographic maps of various scales. In order to determine the nature of the topographic data we require here, we must examine how the data we seek are to be used and what the effects of topography are on the urban fire vulnerability problem. Topographic features are important in assessing urban fire vulnerability in the following ways:

1. Shielding from the thermal radiation emitted by the nuclear fireball.

2. Shielding from the blast wave of the nuclear explosion.

3. Affecting the meteorological parameters.

4. Affecting the subsequent fire spread.

From these, we have ascertained that the data with which we desire to describe the topography of an urban target are:

a. The elevation of the surface of the land (or water).

b. The angle (or steepness) of slopes.

c. The direction (or aspect) of the slopes.

Methods are available, through the use of controlled aerial photography, by which the above topographic data can be quickly obtained for large areas of land with an accuracy sufficient for our purposes. Topographic mapping by ground survey is a slower but more accurate method of obtaining the same information. Use of the obtained data will depend on an understanding of the accuracy of the method or methods used to obtain the data. Topographic maps indicate ground-and water-surface elevations above (or below) mean sea level for any geographic location. Constant elevation levels on these maps are indicated by contour lines whose distance between intervals will vary from map to map.

Topographic features of the ground surface are described by their size, geometry, degree of abruptness, and arrangement in relation to other topographical features. Many words and phrases have been applied to the various degrees of abruptness, such as mountains, hills, mounds, plains, canyons, and valleys. It will not be necessary for us to attempt a complete list of these at this time except to say these are the terms, with an equally large number of adjectives, that are used to describe general topography.

It can be readily observed that the ground covered by U.S. cities is very small compared with the entire U.S. land mass. Most U.S. cities (the majority have under 100,000 population) are relatively flat. (An example of an exception is San Francisco, which is quite hilly.) A nonflat area is one whose elevation changes relatively abruptly with any change in geographical location within the nonflat area. We choose here to consider the surface contours of buildings, vegetation, etc., as aboveground features separately from ground-surface features. If we speak generally about the topography of urban areas, we will note that the arrangement of hills, valleys, etc. about any urban area in a given region is specific and must be individually determined.

The analysis of the effect of topography on urban fire vulnerability may be best performed in conjunction with a city-plan overlay on a topographic map (or photo) that indicates any significant topography within a city or town and also that of the surrounding region. The U.S. Army is currently attempting to classify topographical features in a general way in their work on terrain analysis (landscape geometry). The scale of Army Map Service maps is usually 2½" = 1 mile (detailed view) or about 1/4" = 1 mile (general view). The elevation of a city can be used as a reference level in describing whether other topographical features either rise or fall from this level. For example, Denver is a relatively flat city at a high elevation (about 1 mile) within sight of the much higher Rocky Mountain range. San Francisco, on the other hand, is a relatively hilly, Pacific Coastal urban area, and is surrounded by large bodies of water (ocean and bay) on three sides and by a specific arrangement of outlying moderately high mountains. Los Angeles is characterized by a unique series of canyons, faces the ocean on the west side, and is hemmed in a basin by mountains on the north and east sides.

We have already mentioned that the majority of cities are flat, and the cases where the topographical features within an urban area are severe are rather rare. It seems, therefore, that we can generalize by saying that the most important topographical features we should consider generally lie in the region surrounding a city or urban area. Meaningful generalizations about certain patterns or types of topography that could then be applied to many different but yet similar urban situations in order that the effects of topography on shielding, meteorology, and fire spread may be determined, would be useful.

On the local level, there are several surface features of an urban area to be considered: (1) the unstructured,* unvegetated areas, and (2) the water areas. Vacant land may be the plowed fields adjacent to the urban area, natural sand dunes, graveled areas, sundried ponds, the shorelines of reservoirs whose water lines have receded, empty-unvegetated vacant lots between buildings, or construction sites. Vacant land within an urban area may become structured (new construction, etc.) within a few months, and the plowed vacant areas of surrounding farm land may become vegetated land during the growing and harvest months. These areas characteristically have no fuel value and will not burn. However, there are two parameters associated with these areas that could influence the fire vulnerability of an urban area: (1) the texture of the vacant areas' surface; that is, whether it is firmly packed or loosely packed, (susceptibility to debris production), and (2) the minimum separation distance across the vacant area that thermal radiant energy and/or firebrands could spread fire. The surface of vacant lands (areas) is specified as firm or loose so that the effects of blast-wave debris damage and radiant-heat-energy transmission (from the fireball or from burning fuel) obscuration by airborne dust, sand, etc., of the adjacent structures can be estimated. The analysis of the effect of vacant areas on fire vulnerability is usually performed in conjunction with an overlay of the location, characteristics, and geometry of urban fuels. Vacant areas are fire breaks, and any method of describing how these areas behave as fire breaks or as discontinuities in the urban fuel bed will be of importance to the prediction of fire spread.

A.4.2 Water Areas

Water areas, which are flat, are described in a similar way to vacant areas since they act as fire breaks, but with some differences. The geometry of the water area is useful in calculating the minimum distances thermal radiant energy and/or firebrands would have to travel to spread fire. The geometry of the water area, whether it is circular like some lakes and ponds or quite linear like canals and streams, is important in determining firebrand "jump" distances. The depth of certain water areas should be reported since it will influence the amount of base surge and/or tidal-wave water for certain near or above-water surface bursts. If the water area is contained, such as by a dam or reservoir, it will be important to specify the effect of rupture on the water area and the surrounding area. The flow rate and direction of a water area's flow may be responsible for transporting lighter-than-water fuels downstream following a burst.

Water areas exhibit changes with geographical location and with season in various regions of the U.S. Smaller water areas often dry up in the summer (dry) months, and certain large water areas, such as the

* We consider structures to be anything constructed by man.

Mississippi River, display seasonal periods of flooding. In the colder climates, water areas are frozen over during the winter months.

The albedo (reflection property) of vacant land and water areas is a parameter in regard to its effect on attenuating or enhancing the amount of thermal radiation received on nearby target fuels. Marsh and swamp areas are considered to have the combined properties of both vegetated and water areas.

A.5 STRUCTURES

A.5.1 Identification Criteria and Examples

All urban areas contain structures, which we have defined as anything constructed by man. When we examine aerial photography of urban areas, we are able to identify and classify almost all structures according to whether they are enclosed* or open, whether they have much fuel value (the potential ability of a material to contribute heat to a fire according to an arbitrary scale) or practically no fuel value, and whether they are generally fixed or transient.**

A summary identification of the structures of an urban area with examples is given in Table A.1-B - Structures. The distinction between enclosed and open structures is useful in that enclosed structures, if they burn, will display the behavior of fire in enclosures at some time during the fire; whereas open structures, if they burn, will display the behavior of fires in the open. The criterion for identifying a structure as a building is whether or not the structure has walls and a roof. All buildings occur as rather discrete units; but even though they may have common (party) walls, the number of buildings in an area is usually readily determined from aerial photographs. The significant enclosures of buildings are rooms (regular enclosures) made up of walls, a floor, and a ceiling; halls, stairwells, and irregular enclosures. The dimensions of enclosures will vary considerably from residential to industrial use. Buildings usually have high fuel value, although some have very low

* An enclosure is defined here as a space having certain structural boundaries that restricts meteorological (weather) equilibrium, will tend to conserve heat, combustion products, etc., so as to significantly characterize the fire behavior of the structure at some time during the fire.

** Transient structures are those that can be anticipated to alter locations in a city in some specified time (several days will be used for our purposes because this time is logically the probable minimum time major fuels such as buildings could change location) and; Fixed structures, such as buildings do not alter location in the same specified time period.

fuel value because of the nature of the building construction and contents. Buildings are considered fixed in location because it is unlikely that buildings can be erected or torn down in less than several days.

In addition to buildings in an urban area, there are structures with high fuel value that do not have roofs (may have cover or top) and yet exhibit the fire behavior of irregular enclosed spaces. In this group belong the variety of shapes of liquid and gas fuel storage tanks whose sizes will vary from backyard household butane tanks to huge oil and gas refinery storage tanks. However, fixed empty fuel-storage tanks, or nonfuel-storage tanks, are considered in another category (empty and nonfuel tanks of low fuel value) in that they may have a potential effect on subsequent fire effects irrespective of fuel value and in that their profile to the wind will possibly influence the wind patterns in the city.

The transient structures within an urban area may be classified as having high fuel value and low fuel value. Most vehicles of transportation can be classed as of high fuel value in that they usually contain fuel tanks (gas tanks, oil tanks, coal storage, etc.,) and have upholstery, such as automobiles have, or are transporting materials of high fuel value. There are certain vehicles, such as electric vehicles and empty railroad tank cars, that have been placed in a separate class because of their low fuel value.

The open structures of an urban area may be similarly classed according to whether they are transient or fixed. Transient structures are either light, so as to be blown to a new location by the wind or moved by human beings, or consist of the "rolling" stock of goods that are transported throughout a city by vehicles. Open fixed structures contain a wide variety of construction types and uses from railroad (wood) bridges to coal piles. Open fixed low-fuel value structures similarly display a wide variety of construction types, dimensions, and geometries and are different from the above in the very small amount of fuel value that may be assigned to these structures. Open transient structures of high and low fuel value have the parameters governing the size of the structure for wind dispersal and transportation in common with enclosed transient structures. Open transient structures of high fuel value include human garbage, litter, etc., plus structures that can be transported from one location to another within a city in several days. Low-fuel-value structures are such light nonfuel wastes as aluminum chewing gum wrappers, aluminum foil in garbage, and other low-fuel-value open structures that can be transported by human activity.

Let us now examine each of the classes of structures in order to identify the parameters that may be used to describe the fire vulnerability of each class of structure.

A.5.2 Buildings

The buildings in an urban area are the most important structures contributing to fire vulnerability, as judged by their number and fuel loads.

A.5.2.1 Building Density

One of the most important gross parameters describing buildings is building density, which is expressed as the percent of the total ground area occupied by buildings. Bond,[5] and Bevan and Webster[6] agree that building density is the most important single parameter that determines whether or not a firestorm can develop in an urban area. From an aerial map, it is a relatively easy matter to outline the areas occupied by roofs.

Two methods for determining the building density are in general use: the square-counting method and the area-measuring method.[7] In the square-counting method, a fine-square grid is placed over an aerial photograph or map of the urban area, and the building density is obtained by dividing the total number of squares occupied by buildings by the total ground area. This method is usually employed when the photos indicate unclear detail or when the separations between buildings are uniformly small. In the area-measuring method, the building-roof area and the ground area are actually measured, and the building density is obtained by dividing the building-roof area by the total ground area. It will be important when citing a particular building density to indicate the total ground area to which the density applies, that is, whether it is an average building density for an entire city, for an average use area, or for a single city block.

Building density appears to be strongly related to fireload (lb of combustible per ft^2); this relation has been verified for some cases of World War II incendiary-raid damage to German and Japanese cities.[7] The building density of urban areas can have a wide range of values if one considers an entire urban complex. Building density (should not be confused with "builtupness" which is a combined term for building density, building height and building separation) generally increases up to a point with the "builtupness." Even in the most heavily built-up areas of a city, there must be room left for streets and other non-building use; hence, building density approaches about 75% over medium-sized areas. Hamburg, which is noted for its firestorm, is reported to have had typical blocks with building densities up to 67% and with an average of 30% to 40% in the firestorm area.[8] These building densities are quite high compared with other less "built-up" parts of a city. About 10% seems reasonable as the building density of most typical urban areas (this excludes cities of over 100,000 population, which are in the minority, but of considerable concern to OCD).

The best sources for determining building densities at no cost or small cost are maps supplied by local planning or administrative offices of the city considered. Maps with scales of 1 inch = 50 ft or 1 inch = 100 ft (each map sheet covers 1000 or 2000 ft^2) are usually unsuitable for conveniently determining building densities of large areas. For small communities, it is convenient to use scales of up to about 1 inch = 4000 ft and not less than 1 inch = 1000 ft.

The building density of a city is not a generally available figure, although it may be conveniently obtained. Building density is not usually subject to much change with time for a specific city, since buildings that are torn down are most often replaced by new buildings. However, there are communities that are adding large new residential tracts that may significantly influence average urban area building densities.

A.5.2.2 Building Heights

Building height is spoken of as either the true height, which is the distance from ground level to the top or peak of the roof, or the height from the ground to the eaves (where the roof joins the walls). Both heights are usually obtainable for any building from oblique aerial photography, by aerial photography employing certain shadowing techniques or by survey from the ground. By excluding the geometry of the roof (by using the height to the eaves), however, a more accurate estimate of the number of stories results. A common practice is to estimate the number of stories from the height of the building by assuming that 10 to 12 ft is the height of the average story. Very few cities have many buildings with over 8 stories; 1-, 2-, and 3-storied buildings are the most common. Buildings with more than 8 stories usually occur in areas of very high "builtupness." The height of buildings varies with the city and the location in the city. Los Angeles has very few tall buildings, probably because of use, transportation access, and population density. Certain cities regulate building heights for a variety of reasons, such as earthquakes (San Francisco, for example, regulates the height of nonearthquake-resistant buildings), or depth of bedrock, or fill, or use (see appropriate building codes, such as the Uniform Building Code by the International Conference of Building Officials, 1964 edition. This code presents specifications by occupancy for a. Construction type, b. Fire zones, c. Area limitations and/or increases, d. Number of stories, e. Maximum height of buildings, f. Location on property, g. Design, and h. Detailed occupancy and construction requirements. This code was established to ensure the development of sound economic basis for future growth of cities through unbiased and equitable treatment of structural design and fire hazards. A map of the U.S. showing major areas of approximately equal seismic probability shows 5 distinct areas of potential major earthquake damage, 4 areas of moderate damage, 4 areas of minor damage, and 2 areas of no damage).

A.5.2.3 Building Volume

An estimate of building volume is readily obtained by multiplying the building height by the roof area. The average volume of buildings in any area is obtained by multiplying the ground area covered by buildings by the average height of all the buildings. Building volume has been previously used in wartime analysis[7] of the fire vulnerability of both German and Japanese cities based on the idea that building volume had a stronger relationship to a building's fire load than building density. For a large number of analyses, building volume was shown to be important, even though a consistent correlation between building volume and fire spread could not be shown for all cases. The building volume of a single-story building on a large area can have the same volume as a many-storied building.

A.5.2.4 Building Separation

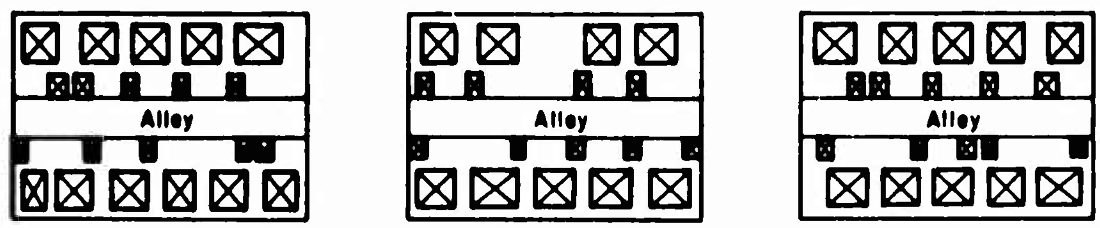
Building separation refers to the average distance separating the walls of adjacent buildings and generally decreases up to a point with increase in building density. Building separation is conveniently measured from aerial photographs of a city. In the downtown area of most cities, the buildings along one side of the street adjoin each other with common walls or narrow separation distances. These buildings are separated from the buildings across the street by the width of the street plus two sidewalks. Hence, building separation in downtown areas can be gauged by the widths of streets, alleys, and freeways, and in a few specific local areas by rivers or parks. As one moves from the downtown built-up area, the separation distance between buildings usually increases and the amount of unstructured ground generally increases. Also, there are few areas of vacant land and vegetated areas in heavily built-up areas of a city.

What we seek is the average separation between adjacent walls of a building, houses, etc., for the size of area being considered. The orientation of residential houses in a tract often determines the separation distance in a subarea of an urban area. Normally, houses and stores are built facing the street; hence, the separation distance at either side of the buildings is often less than the separation distances at the front and rear of the buildings.

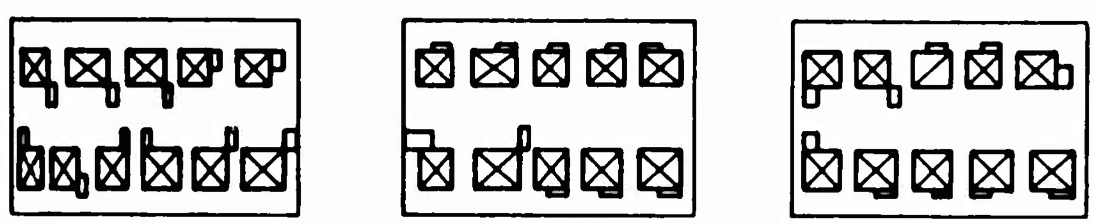
A.5.2.5 Arrangement of Buildings

Since buildings normally face the street, their arrangement may often be expressed by studying the various city street patterns. These patterns are influenced to a large degree by the age of a city, although the age of a city can usually not be determined from such patterns alone. An example of the arrangement of houses in an older residential community is the rectangular or square block with homes lining the streets and an

alley dividing the block in half. See the following sketch:

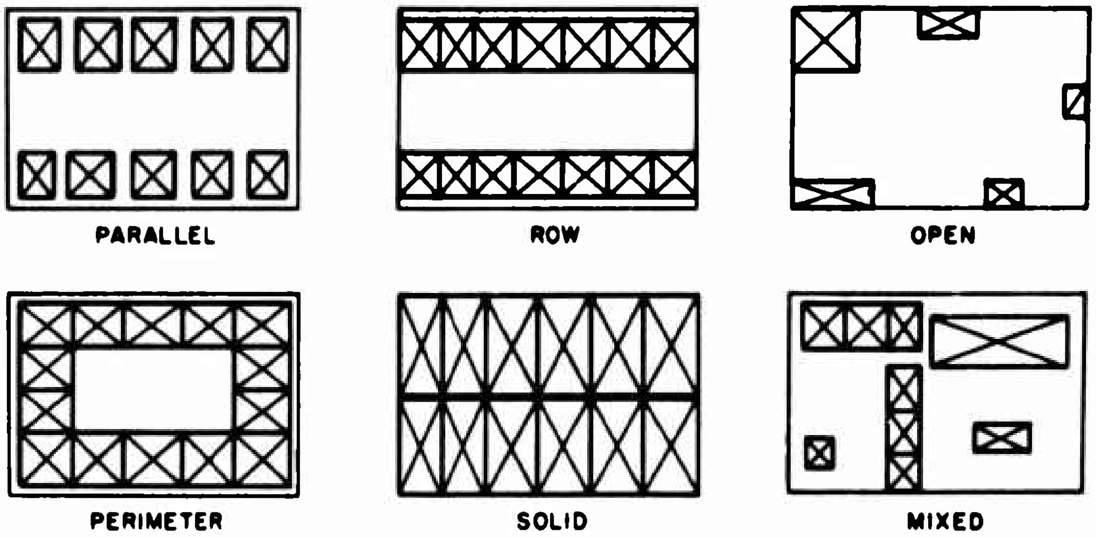


These houses are normally quite close to the street. Such a house has a small front yard but a rather large back yard containing a garage. Generally, the alley of one block is continuous with that of the next block. In more modern communities, the alley has been eliminated, and the houses are built with the garage entrance on the street (generally attached to the house) or with an access driveway from the front to the rear, so that the front yard is larger and the distance from the front of the house to the street is greater. See sketch below.



City street patterns may be generalized into the several standard types shown in Figure A.1. Generally, the grid, offset, circle, and contour patterns are characteristic of older cities or older city areas. A city is more often composed of patterns that are combinations of several of the standard patterns. Further information on city and suburban street patterns, in addition to recent generalized descriptive information, is contained in the September, 1965 <u>Scientific</u> <u>American</u> magazine whose theme is "Cities."

The size of a city block is quite variable in dimensions and shape. Streets are usually two lanes wide, and few exceed 8 lanes in width. The patterns of building construction on city blocks may also be categorized into a variety of types, some of which are shown in the following sketches:



These patterns are often determined by the habits and customs of the people. The arrangement of buildings in an urban area is basically described according to the following criteria:

a. Distances to adjoining buildings in four directions (narrowest point between two buildings).

b. Angles of walls to adjacent facing walls of adjoining buildings.

c. Directions of the length and width of buildings in a block.

d. Geometry and dimensions of the block.

e. Number of buildings in the block.

f. Number of buildings with dimensions similarly oriented (for instance, most buildings in a typical block have the short dimension (width) parallel with the streets).

g. Location in the city block of buildings according to height, length, and width (geometry) (to determine whether the heights of some buildings deviate markedly from the average).

h. Orientation of blocks to each other (for instance, whether blocks of similar patterns "line up" or whether they "oppose" each other by any of the above criteria).

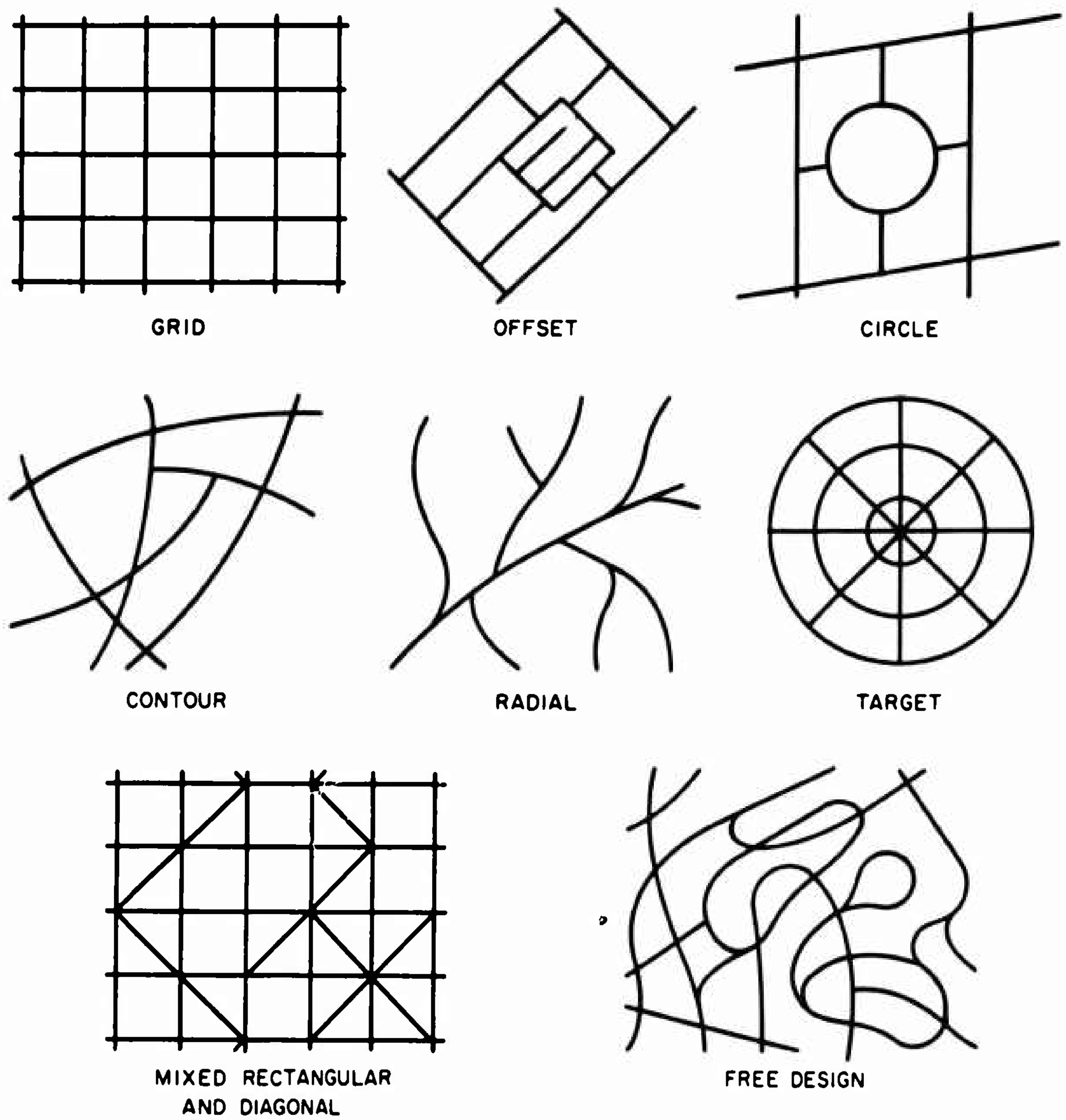


Fig. A.1 Standard Types of City Street Patterns

A.5.2.6 Standard Types of Building Construction

The construction of buildings may be classed according to their ability to withstand fire, which depends for the most part, upon the constructional materials. Five standard types of building construction are recognized by the NFPA (National Fire Protection Association): fire-resistive, heavy timber, noncombustible,* ordinary, and wood frame. These types, which are completely described in NFPA No. 220,[9] are summarized in Table A.2.

Fire-resistive construction is that type in which the structural members, including walls, partitions, columns, and floor and roof construction, are of noncombustible material with fire-resistance ratings of not less than those specified in Table A.2. A fire-resistive building is structurally able to resist fire damage and collapse when exposed to temperatures of the Standard Time-Temperature Curve (Fig. A.2) for the period of time indicated by its classification.

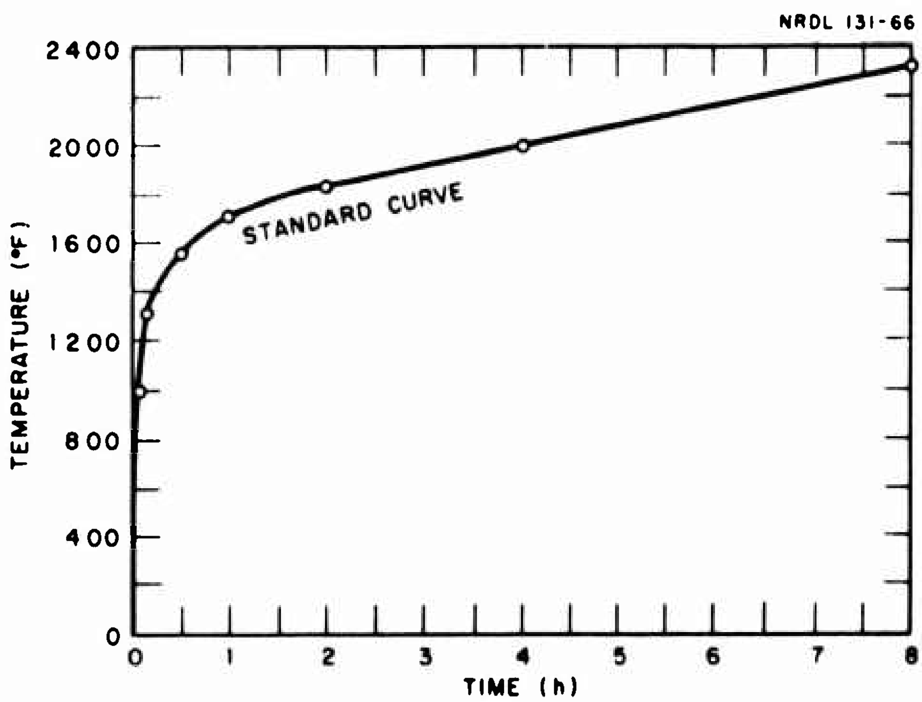


Fig. A.2 Standard Time-Temperature Curve[9]

* refers to a material or structure which will not burn under specified conditions but does not indicate ease of ignition, burning intensity, or rate of burning (see footnote on p. 117).

TABLE A.2

Fire-Resistance Ratings of Structural Members for Fire-Resistive Buildings of 3-Hr and 2-Hr Classifications*

Structural Member	Classification 3-Hr	Classification 2-Hr
Bearing walls or portions of walls (exterior or interior)	4	3
Principal supporting members, including columns, trusses, girders, and beams for more than one floor or roof	4	3
Principal supporting members, including columns, trusses, girders, and beams for one floor or roof only	3	2
Secondary floor construction members, such as beams, slabs, and joists not affecting the stability of the building	3	2
Interior partitions enclosing stairways and other openings through floors	2	2
Secondary roof construction members, such as beams, purlins, and slabs not affecting the stability of the building	2	1½
Nonbearing walls or portions of walls, exterior or interior	Noncombustible	Noncombustible

* NFPA Handbook, 12th Edition (Ref. 9, p. 8-148)

This curve is an approximation of the maximum severity of a fire likely to occur without firefighting in the complete burnout of a wood-joisted brick building and its contents (which in the tests were actually waste lumber and similar materials of caloric value of about 7000 to 8000 Btu/lb). In actual building burns by NBS (National Bureau of Standards) for the purpose of determining how close they could duplicate the curve, NBS found that the temperature rise during the first part of the test was more rapid than that represented by the curve. They concluded, however, that the overall experimental results indicated that the curve approximated the maximum fire severity resulting from the destruction of such a building and its contents for the length of time indicated by its classification. The floor coverings of the test building were enclosed with fire-resistive partitions, the roof construction was fire-resistive or protected by fire-resistive ceiling assembly, and the interior and exterior nonbearing walls were noncombustible; but did not necessarily possess any specified fire resistance.

Heavy-Timber Construction is that type of construction in which the bearing walls and portions of walls have a minimum resistance of 2-hr to fire and a stability for that time under fire conditions. The nonbearing exterior walls are also noncombustible. The columns, beams, and girders are commonly heavy timber, and the floor and roof construction is wood. A building with wood columns is classed as heavy-timber construction if the columns are greater than 8 inches in any dimensions and if the wood beams and girders are greater than 6 inches in the least dimension and greater than 10 inches in depth. The framing members must be greater than 4 x 6 inches unless the spaced members are two pieces that together are at least 3 inches thick when blocked solidly throughout their intervening spaces or unless such spaces are tightly closed by a continuous wood plate greater than 2 inches thick secured to the underside of the members. Roof decks must be of planks greater than 3 inches wide set on edge and laid as required for floors. Beams and girders supporting roof loads only must be greater than 6 inches in the last dimension.

Heavy-timber construction was becoming less common in the U. S. because other structural materials were more available and economical; but it was revived recently, since new techniques of forming large-dimension timber have been developed. Structures built with formed timber belong to the type of heavy-timber construction if they meet the specifications of heavy-timber construction. This type of construction is typically slow-burning because of its small ratio of exposed surface to total volume of combustible members and because of its large size and mass of planks and timbers. The various details of heavy-timber construction may be obtained from the National Lumber Manufacturers Association.

Noncombustible construction is that type of construction in which the walls, partitions, and structural members are of noncombustible construction that does not qualify as fire-resistive construction. Noncombustible buildings are those structures that will not contribute fuel to a fire. A protected noncombustible building is one of such construction that the bearing exterior or interior walls or the bearing parts thereof are of noncombustible construction having at least a 2-hr fire resistance and stability under fire conditions; roof, floor construction and their supports have 1-hr fire resistance. Openings through floors, such as stairways, must be enclosed in partitions having at least a 1-hr fire resistance. Noncombustible materials fall into three classes according to NFPA No. 220:[9]

1. Materials no part of which will ignite and burn when subjected to fire.

2. Materials having a structural base of noncombustible material as in 1, with a surface not over 1/8 inch thick that has a flame-spread rating (tunnel test) not higher than 50. Flame-spread rating refers to ratings obtained in tests conducted according to NFPA No. 255,[9] in which flame spread is rated on a scale where cement asbestos board is 0, and red oak is 100.

3. Materials, other than those described in 1 or 2, that have a flame-spread rating no greater than 25 without evidence of continued progressive combustion and are of such composition that surfaces that would be exposed by cutting through the material in any way would not have a flame-spread rating higher than 25 without evidence of continued progressive combustion.

Typical noncombustible constructed buildings are metal-framed, metal-clad buildings. Other materials commonly used are masonry, clay products, iron, steel, aluminum, and mineral materials that are either mixed and applied on the job, or prefabricated into planks, sheets, or boards. To meet the definition, bearing exterior walls usually will have masonry units (concrete or cinder blocks), brick, tile, or reinforced concrete. Nonbearing exterior walls are not required to be fire resistant, but must be noncombustible. The structural framing in exterior walls must have a 2-hr fire resistance. The floor and roof could be open-web steel joists supporting a reinforced concrete wire-lath floor or roof deck and surfaced on the underside of the joists with wallboard or coreboard attached to steel channels. Partitions enclosing floor openings could be steel studs covered on each side with metal lath and plaster.

Ordinary construction is that type of construction in which the exterior bearing walls or the bearing parts of exterior walls are of noncombustible construction having at least a 2-hr fire resistance and

a stability under fire conditions; nonbearing exterior walls are of noncombustible construction; roofs, floors, and interior framing are wholly or partly of wood (or other combustible material) of smaller dimensions than required for heavy-timber construction. The nonbearing exterior walls and bearing walls or bearing parts of walls may be required to fall into this type. "Protected Ordinary Construction" is that in which the roof, floors, and their supports have a 1-hr fire resistance, and stairways and other openings through floors are enclosed with partitions having a 1-hr fire resistance.

Other names for ordinary construction are brick, wood-joisted, and brick joisted construction. Open-joist construction is found more often in industrial buildings, where appearance is not a factor, which increases the amount of wood exposed. If interior combustible structural members are exposed, it is called open-joist construction. The difference between open-joist and heavy-timber construction is in the dimensions of the wood used and in the joist-channels (pockets between joists) of open-joist construction and the relatively flat ceilings in plank-and-timber construction.

The ability of ordinary construction to withstand an interior fire or to confine fire spread to one area is no better than the degree of resistance given to its combustible structural components. Because this type of construction is structurally adaptable to occupancies that have moderate fire loads, ordinary construction was, until recently, the most common type of construction for (1) mercantile and office buildings; (2) multiple-occupancy habitational buildings, such as hotels, apartment houses; and (3) schools, churches, and other institutional occupancies, and for this reason dominated in congested areas of most U.S. cities.

An ordinary-construction building differs from fire-resistive and noncombustible buildings in that it has concealed wall and ceiling spaces that contain combustible materials. Ordinary-construction materials used in exterior walls are usually brick, reinforced concrete, concrete, and masonry units. The National Building Code specifies that the bearing ends of joists and timbers for this type of construction be at least 3 inches thick. Wooden floors composed of a subflooring overlaid with finish flooring having a nominal thickness of 2 inches are common in ordinary construction. Also used extensively is subflooring topped with plywood and covered with asphalt, rubber, plastic tile, or other decorative covering. With respect to the height and area limitations of many building codes, ordinary construction occurs less than heavy-timber construction and more than wood-frame construction in the areas permitted.

Wood-frame construction is that type of construction in which the exterior walls, partitions, floor and roof construction, and their supports are of wood or other combustible materials and the construction does not qualify as heavy-timber or ordinary construction. This type of

construction is called "Protected Wood-Frame Construction" when the roof and floor construction and their supports have a 1-hr fire resistance, and stairways and other openings through floors are enclosed with partitions having a 1-hr fire resistance. This type of construction is nicknamed "frame"; it differs from ordinary construction (brick, wood-joisted) in only one respect: the construction of the exterior walls. It can be assumed that conventional-habitational and other wood structures normally have interior-finish materials that provide protection to structural members to some degree. Basically, exterior wood wall construction consists of vertical wood studs, commonly 2 x 4 inches with 1 inch boards nailed to the studs and with an exterior covering of wood siding. Many variations exist in exterior-wall construction: various composition boards may be used. The following list contains some of the more common kinds of frame-construction materials:

a. Wood shingles, clapboards, matched boards; usually has building paper between it and the exterior sheathing.

b. Brick veneer--consists of a single thickness of brick around a wood-frame house; depends on bonding to the wood for stability.

c. Brick-nogged walls--usually found in old buildings in which brick is laid solid between wood studs.

d. Metal-clad construction--sheet metal nailed over wood siding.

e. Metal clapboards and shingles--applied directly over woodsheathing or over an existing wall covering.

f. Skeleton metal-clad construction--corrugated iron or other metal directly attached to wood frame without intervening boards.

g. Cement-asbestos corrugated sheets--similar to metal-clad construction and skeleton metal-clad construction.

h. Asphalt-composition siding--a finish simulating brick or stone.

i. Stucco--cement plaster on lath or fibreboard over wood-frame construction.

j. Prefabricated plywood walls--various types are essentially equivalent to the basic type of wood studs, boards, and wood siding.

It should be noted that heavy-timber construction and ordinary construction are often grouped together as masonry-wall and wood-type structures with masonry load-bearing walls, interior framing, and wood

floors and walls. Complete details of building construction types, limitations of construction according to six typical building codes, surveys of building contents for typical occupancies, and fire-resistance rating for building constructions and materials may be found in Ref. 10.

A.5.2.7 Building Fireload

The combustible* structural elements and the combustible contents of a building may be expressed as the fireload of the building, (expressed as weight of combustible per area). Since the weight of combustibles alone is insufficient for estimating the heat content, the amount of heat potentially liberated from any given combustible (calorie values) must be known. A survey[11] has been made of combustible contents in buildings in which the amounts of combustibles were obtained by weighing furniture, equipment, goods, and other combustible contents in sufficient quantity to enable the total weight of such material in each area to be computed. No combustible structural elements were included because they are a part of the building itself. References 10 and 11 (also see Ref. 9) report building fireloads of various occupancies. See Table A.3.

A.5.2.8 Building Occupancy and Fireloading Vs Expected Fire Severity and Duration

Figure A.3, from Ref. 9, suggests a possible classification of fire loading by fire severity and duration. The curved lines indicate the severity expected for the various occupancies and fireloading. (See Table A.4.) The straight lines indicate the fire duration based on fireloading by occupancy. There is no direct relationship between the curved and straight lines; but, for example, 10 lb of combustibles/ft^2 will produce a 90-min fire in a "C" occupancy, and a moderate fire severity following the Time-Temperature Curve "C" might be expected.

The British[9] have graded building occupancies as low, moderate and high fireloads in terms of Btu/ft^2. See Table A.5. These fireloads indicate occupancies that are approximately equivalent to those represented by the occupancies of Table A.4 and time-temperature curves of Fig. A.3.

Most fireloading studies have dealt with the fireload of contents of buildings, and only a small amount of survey work has been performed for the fireloads of various types of building construction elements alone. Buildings can be classified according to occupancy and construction type and the fireloads per story (lb/ft^2) can be obtained for buildings of various

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* A relative term referring to any material that can burn; some materials change their combustibility, for example, with a change in the state of subdivision; structural steel is noncombustible, whereas steel wool is combustible.

TABLE A.3

Average Amounts of Combustibles Per Ft^2 of Floor Area[10,11]

(Contents: finished flooring, interior finish, and trim)

Occupancy	Percent of Total Floor Area	Range of Combustible Contents (Lb/Ft^2)
Printing Plant	36.7 27.8 35.5	0.0-14.9 15.0-49.9 50.0-100+
Newspaper Plant	67.6 30.2 2.2	0.0-4.9 15.0-49.9 50.0-100
Department Store A*	12.6 76.6 10.8	0.0-4.9 5.0-14.9 15.0-40+
Department Store B*	7.8 78.4 13.8	0.0-4.9 5.0-14.9 15.0-40+
Clothing Factory A	35.3 53.6 11.1	0.0-9.9 10.0-14.9 15.0-30
Clothing Factory B	85.7 5.7 8.6	0.0-9.9 10.0-14.9 15.0-40
Mattress Factory A	10.8 67.1 22.1	0.0-4.9 5.0-14.9 15.0-50
Mattress Factory B	7.9 46.3 45.8	0.0-4.9 5.0-14.9 15.0-100+

* A and B refer to distinct surveys performed on similar occupancies

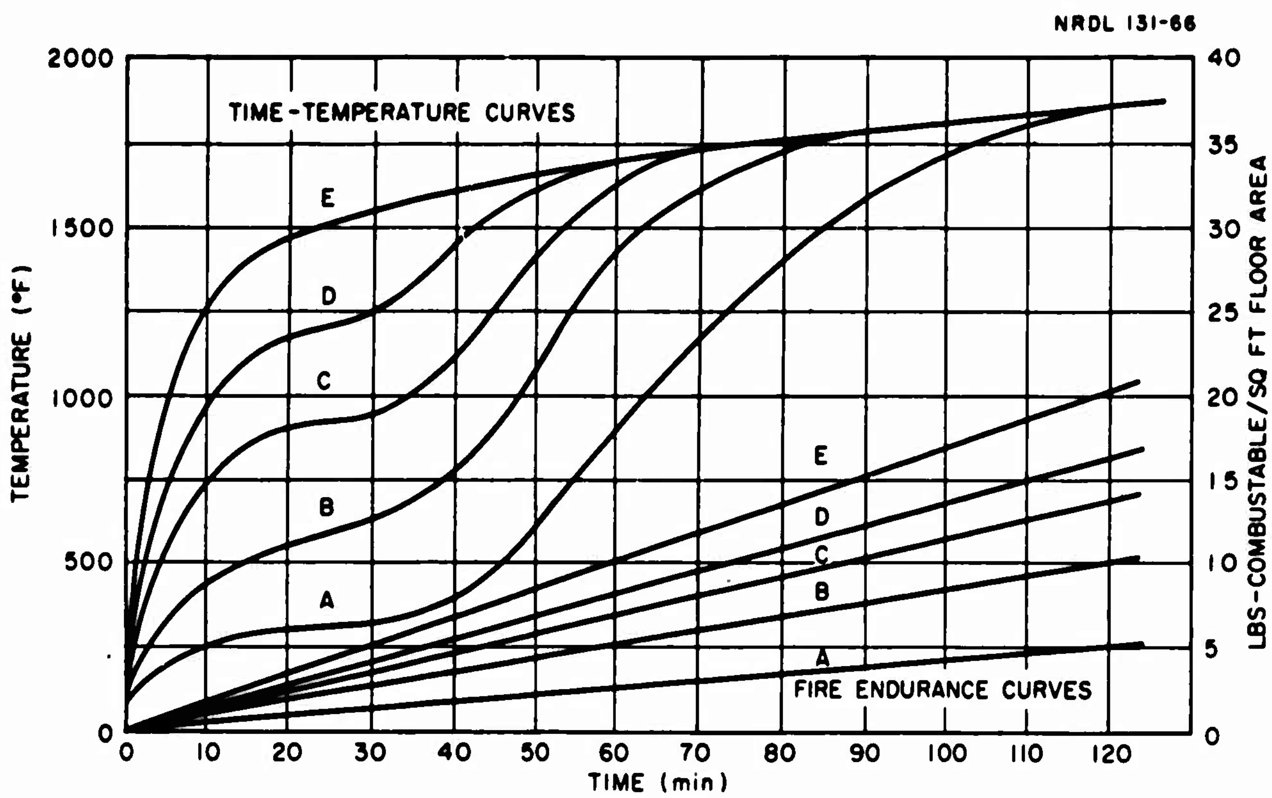
TABLE A.3 (Cont.)

Occupancy	Percent of Total Floor Area	Range of Combustible Contents (Lb/Ft^2)
Furniture Factory A	1.5 81.4 17.1	0.0-9.9 10.0-29.9 30.0-65+
Furniture Factory B	54.7 37.3 8.0	0.0-9.9 10.0-29.9 30.0-65+
Warehouse A*	86.3 13.7	0.0-29.9 30-75
Warehouse B*	18.1 50.9 31.0	0.0-29.9 30.0-74.9 75.0-2.57
High School A (Public)	66.4 25.4 8.2	0.0-4.9 5.0-9.9 10.0-288**
High School B (Public)	32.6 64.1 3.3	0.0-4.9 5.5-9.9 10.0-256***
Offices	59.2 19.2 21.6	0.0-4.9 15.0-29.9 30.0-86
Hospital (Med. and Surg. Bldg)	82.1 17.0 .9	0.0-4.9 5.0-14.9 15.0-20+
Apartments	100.0	10.0 (average range)

* See footnote on p. 118.

** Includes fireloading of storage areas: 25% of floor area ranging from 25 to 100 lb/ft^2 for general storage and 0.2% at 288 lb/ft^2 for textbook storage.

*** Includes 0.3% of floor area at 256 lb/ft^2 for textbook storage.



(See Table A.4 for Definition of Curve Labels.)

Fig. A.3 Possible Classification of Fireloading by Fire Severity and Duration[9]

TABLE A.4

Expected Fire Severity by Building Occupancy[9]

Slight (Time-Temp. Curve A):

Well-arranged office, metal furniture, noncombustible building.
Welding areas containing slight amount of combustibles.
Noncombustible power house.
Noncombustible buildings, slight amount of combustible occupancy.

Moderate (Time-Temp. Curve B):

Cotton and waste-paper storage (baled) and well-arranged, noncombustible building.
Paper-making processes, noncombustible building.
Noncombustible institutional buildings with combustible occupancy.

Moderately Severe (Time-Temp. Curve C):

Well-arranged combustible storage, such as wooden patterns and noncombustible buildings.
Machine shop having noncombustible floors.

Severe (Time-Temp. Curve D):

Manufacturing areas, combustible products, noncombustible building.
Congested combustible storage areas, noncombustible building.

Severe--Standard Fire Exposure (Time-Temp. Curve E):

Flammable liquids.
Woodworking areas.
Office, combustible furniture, and buildings.
Paper working, printing, etc.
Furniture manufacturing and finishing.
Machine shop having combustible floors.

TABLE A.5

Fireloads by Building Occupancy in Btu/Ft^2

Low Fireload (Curve A)	Occupancy has no more than 100,000 Btu/ft^2 for net floor area in any compartment, and an average of 200,000 Btu/ft^2 on limited isolated areas. Examples: offices, restaurants, hotels, hospitals, schools, museums, public libraries, and institutional and administrative buildings.
Moderate or Normal Fireload (Curves B, C, D)	Occupancy has more than 100,000 Btu/ft^2 but not more than 200,000 Btu/ft^2 for net floor area in any compartment; no limited isolated areas with an average over 400,000 Btu/ft^2. Examples: retail shops, factories, and workshops.
High Fireload (Curve E)	Occupancy has over 200,000 Btu/ft^2 but not over 400,000 Btu/ft^2 for net floor area in any compartment; no limited isolated areas over 800,000 Btu/ft^2. Examples: warehouse and other buildings used for storage in bulk of commodities of a recognized nonhazardous nature.

occupancy and construction type, according to the number of stories, number of feet/story, the floor area in ft^2/story, the total wall area in ft^2/story, the window size in ft^2/window, and the percent of window area/wall area. They can also be obtained for contents of buildings only and for building elements only. Waterman et al.[12] uses figures of 2.2 and 2.8 lb/ft^2 for floor fireload of the contents in experimental full-scale building fires, whereas the most often quoted figure is that given by NBS of about 10 lb/ft^2 for about the same dwellings.

A.5.2.9 Building Roofs

Roofs in an urban area identify buildings and have significance as a target parameter in that:

1. Roofs contribute in various degrees to firebrand formation and fire spread.

2. Because of their location on top of buildings, roofs are the only surfaces of a building in direct view of the fireball for certain high-altitude nuclear explosions.

3. Roofs are supported by roof assemblies that must be described in order to ascertain potential total destruction of a building, which is usually taken as the collapse of the roof (except where fires are isolated in the top floors of multistory buildings).

4. The geometrical profile of roofs facing the wind will alter local wind patterns over a building.

5. Roof assemblies have concealed spaces (attics, etc.,) whose dimensions, ventilation, and geometry are considerably different from the rooms of the building. Such concealed spaces are usually poorly ventilated.

The Western Actuarial Bureau recognizes several standard types of roofs (see Fig. A.4), and there are many variations of these if one begins to examine the details of construction.[9] The types of building roofs vary with geographical location, age, climate, load to be supported, heat-insulating properties, design, suitability for utilities, and a number of other parameters. The pitch of a roof is used to describe the angle that the surface of the roof makes with the level ground. The pitch may be described as either (a) flat (0°), (b) slight ($< 30^\circ$), (c) steep ($> 30^\circ$). Generally, roof coverings are considered constructionally apart from the supporting roof assembly. The flat roof, whose roof-assembly surface parallels the ceiling(s) of the room(s) below, should be mentioned. Often in these cases, the concealed space between the roof and the ceiling(s) of the room(s) below is quite small.

Examples, from Ref. 9, of roof framing systems are: lightweight precast planks, channel and double-tee slabs, poured-in-place roof decks, corrugated roof sheets, corrugated glass or translucent plastic panels, and wood decking.

The coverings over various roof assemblies vary from the well-known highly combustible wood shingles to relatively noncombustible "built-up" coverings. Wood shingles are considered particularly hazardous because they are readily ignited by small sparks, larger firebrands or radiated

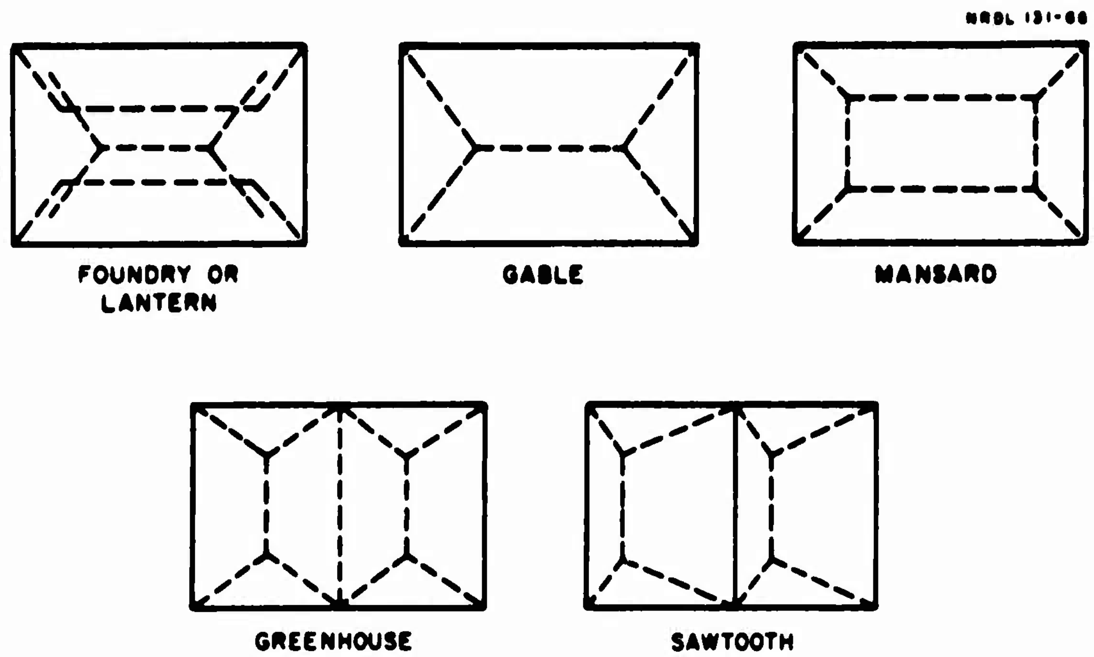


Fig. A.4 Several Types of Roofs

heat, and are themselves a source of firebrands. This type of roof covering is prohibited in certain cities and towns (San Francisco prohibits wood shingle roofs). In certain areas where they are not prohibited, examples can be cited where wood shingles have contributed significantly to the spread of a large fire (Bel-Air 1961 conflagration in Southern California). Roof coverings, such as asphalt shingles can melt and drip through certain roof assemblies to the rooms beneath. The NFPA[9] has classified roof coverings into three exposure classes:

A. Effective against severe exposure.

B. Effective against moderate exposure.

C. Effective against light exposure.

Another classification of roof coverings is according to the degree of protection they offer against direct flames and radiation exposure, and their potential production of burning firebrands. Only an approximate correlation can be made between the two classification systems. A complete discussion of the various roof-covering classifications may be

found in Ref. 10. Wilson[13] has demonstrated how the presence of highly combustible materials, such as asphalt in the vapor seal and/or adhesive between the insulation and the metal deck, governs the spread of fire beneath the roof within the building when the underside of the roof is exposed to fire.

Over 80% of the roofing in the U.S. consists of asphalt shingles.[14] In a survey by Cullen[14] of 54 Army, Navy, and Air Force installations from Maine to Florida, 36 (or 67%) reported wind damage to asphalt-shingle roofing. Strohan and Cullen reports that heavier asphalt shingles have better resistance to wind, but that in the event of strong winds, free-tab shingles of any weight may be vulnerable to damage if the tabs are not restrained by locking devices or, if in recent years, pressure or heat-sensitive adhesives have not been applied to hold the tabs down.

A.5.2.10 Building Openings

An opening is any gap in the structural continuity of some structural enclosure that permits the joining of enclosures with one or more interior enclosures or the exterior. Such joining results in an increased total enclosed volume consisting of the volume of the joined enclosures. Openings in buildings may be classified according to the direction in which they spread fire: vertically or horizontally. Examples of vertical openings are those that open directly through the floor and those that open into enclosures around stairs, elevators, dumbwaiters, chutes, and so forth. Examples of horizontal openings are those in the walls or partitions dividing any floor of a building into rooms, corridors, etc., and also the openings in exterior walls, such as doors and windows. The important parameters used to describe openings are (1) the area of the opening, (2) the dimensions of the opening, (3) the location and number of openings relative to exterior and interior combustibles (for example, windows in a room or vents of an enclosure), (4) the cover over the opening, if any, (5) the resistance of the opening covers to fire, and (6) the number of enclosures sharing a particular opening. The number of openings (together with their location, area, dimensions, and cover) should be specified per exterior wall of a building. Windows may be classified according to whether they are simple opening, vertical-vane opening, or horizontal-vane opening. See Fig. A.5

The flow of air through each of the illustrated window types has been analyzed by Holleman.[15] In general, air is likely to flow in any direction through these openings depending on the surrounding pressures at the various sides of the opening. Air will flow straight through the opening only if the pressures are symmetrical (perpendicular to the window wall). Usually, winds are unsymmetrical so that air will flow at some other angle than perpendicular. The degree of closure in some of the window types will deflect the direction of the wind in or out of a building.

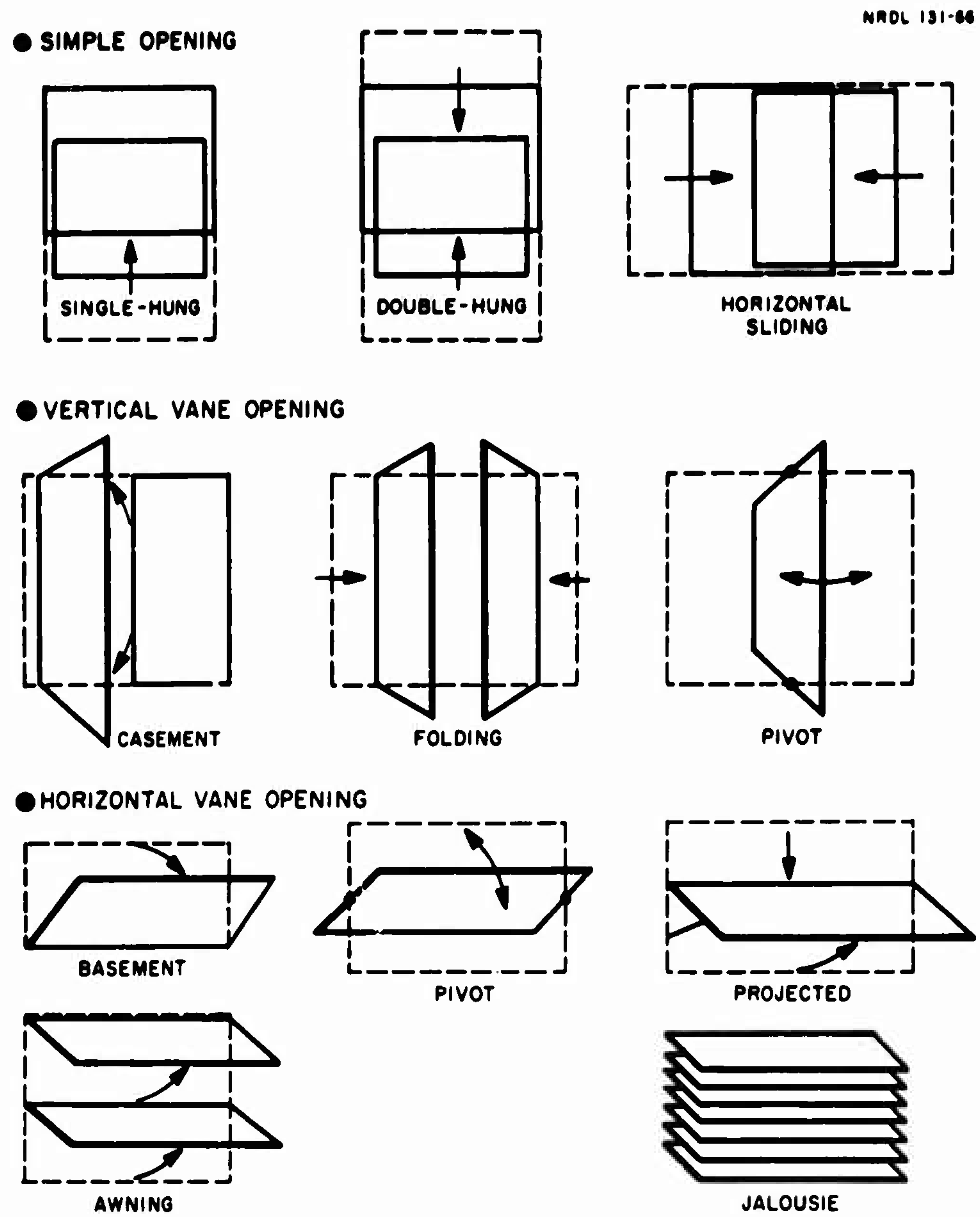


Fig. A.5 Classification of Windows by Type of Openings [15]

The covers of openings are of a variety of materials, such as glass, wired glass, glass blocks, and wood and steel doors. Reference 9 (NFPA No. 80) identifies the openings commonly encountered into six classes:

Openings in walls separating buildings or dividing a single building into fire areas.

Openings in enclosures of vertical communication through the building, such as stairs and elevators.

Openings in corridor and room partitions.

Openings in exterior walls subject to severe fire exposure from outside the building.

Openings in exterior walls subject to moderate fire exposure from outside the building.

Openings in exterior walls subject to light fire exposure from outside the building.

Each floor of a building resists the vertical spread of fire, and hence the description of openings like stairways, elevators, and ventilation shafts (cr shafts for pipes, etc.,) should include the resistance to pressure and heat of enclosures with vertical openings. Similarly, for horizontal openings [openings in partition and exterior walls do not include the enclosures about vertical openings], the resistance of doors and windows to pressure and heat should be described. For fireloadings the resistance to fire of the various types of opening covers, floors, and walls are generally available from the NFPA. The description of openings should specify whether the window and door covers are glass (various strengths), aluminum shades, aluminum or steel venetian blinds, various sized mesh (18 x 14, 20 x 20, or 24 x 24 are common screen meshes) insect screens, paper draw curtains, or wooden shutters.

A.5.2.11 Building Response to Blast

Since the classification of building construction types presented previously is slanted toward fire vulnerability, it might be useful to present here a classification of buildings according to their response to blast. It is important to know which buildings fail structurally (either partially or totally) and how long it takes them to fail under any burst parameters. We are interested here in grouping buildings according to their behavior to blast. Reference 16 has grouped buildings as nonductile (masonry, wood, etc.,) or ductile (steel framed). We would also like to know how to describe the arrangement and sizes of buildings with respect to potential blast damage. Reference 16 describes the role of fire on the production and destruction of debris. United Research

Services has also developed relationships between blast overpressure and the amount of debris (percent of total building material) produced by air blast for 20-KT and weapons of other yields and the following six classes of structures (refer to Fig. A.6):

1. Industrial structures consisting of a heavy steel framework covered by lightweight wall and roofing materials (termed steel frame, industrial, light).

2. Industrial structures consisting of a heavy steel framework (used to support a heavy crane*) covered by lightweight wall and roofing materials (steel frame, industrial, heavy).

3. Multistory structures with either steel or reinforced concrete framework constructed to withstand earthquake loads (aseismic design) (steel or reinforced concrete frame, commercial, heavy).

4. Multistory structures with either steel or reinforced concrete framework not specifically designed to withstand earthquake loads and covered with relatively lightweight curtain-wall panels (steel or reinforced concrete frame, commercial light).

5. Structures with unreinforced brick or masonry load-bearing walls (brick load bearing).

6. Structures with wooden frames and light walls, not designed for industrial use (wood frame).

Buildings in the first class are typical of buildings in industrial areas, where the framework is steel, covered with either corrugated steel, corrugated asbestos, or flat sheetmetal panels. In this class are included all buildings in which the wall panels provide all the necessary support for the roof, etc. Entire buildings or their elements can be divided into two groups: those that fail due to rapidly applied diffraction-phase loadings and those that fail only under longer time, transition, and drag-phase loadings.[11] The most important characteristics of a target that determine the group in which it should be placed are its natural period relative to the shock-wave-loading duration, and its ability to retain useful load-carrying characteristics after it has exceeded its elastic yield point (which is measured by ductility, the ratio of breaking strain to strain at the elastic yield point).[16]

It seems to us that there are buildings in urban areas that do not readily fall into the proposed classifications. The studies of debris production usually consider only the debris produced by the structural elements of the building itself and not the building contents. United Research Services, the Ballistics Research Laboratory, and the Naval Civil Engineering Laboratory have succeeded in developing models of structures that correctly respond to blast loadings within city complexes.[16]

* Where live loads, such as cranes and machinery, produce impact or vibration, 25% or more is added to static loads.

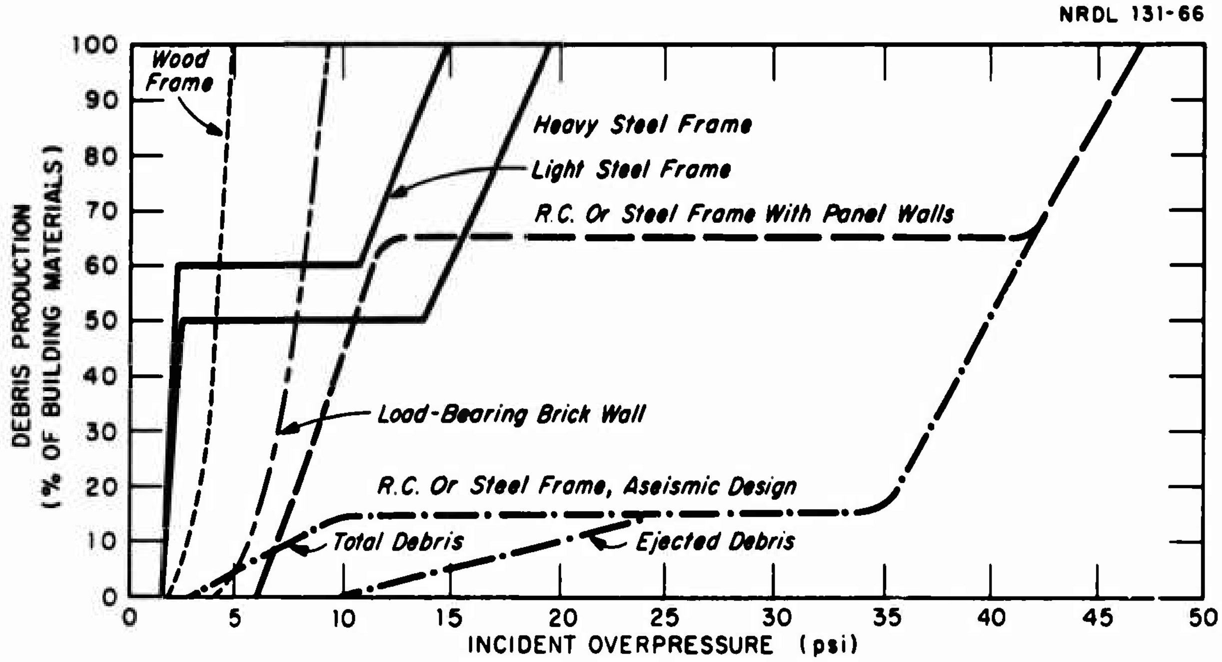


Fig. A.6 Debris Production Vs Overpressure for 20 KT Weapon (From Ref. 16)

A.5.2.12 Locations of Potential Secondary and Tertiary Ignitions

Specification of the locations of potential secondary and tertiary ignitions appears desirable. Secondary ignitions are those caused by air blast and its effects. Tertiary ignitions are those caused by human activity; in addition to an expected increase in the general accident rate during an attack situation, fires are likely as a result of improper shutdown or nonattendance of industrial equipment or home appliances.

It is desirable in specifying secondary ignition sites in this section to indicate equipment and facilities in buildings that could cause ignitions due to blast: appliances, meters, heated tools, panel boards, wiring, transformers, fixtures, lamps, sockets, switches, motors, TV sets, radios, heating equipment (such as fuel-oil, gas, and coal heaters), heat-distributing ventilation systems (such as chimneys and stacks), refrigeration and air-conditioning systems, other electrical equipment, ovens, kilns, etc. Buildings unaffected by blast can be affected by secondary ignitions in that power surges, as the source is disrupted, may cause overheating of some equipment (indirect blast-caused fires).

Tertiary ignitions may possibly be described by determining those areas where people will likely be working with heated tools, motors, machinery, etc., which present a fire hazard if unattended or which could produce ignition if misused as a result of surprise nuclear attack. Electricity becomes a hazard through arcing or overheating. Any switch carrying a current will produce an arc when the current is interrupted, and the arc could ignite a combustible material in the vicinity. What is required, therefore, is a specification not only of the locations where arcing or overheating (either blast or people-caused) could occur, but also whether combustibles are in the vicinity of the locations, whether ambient conditions will exist for ignition, and whether ignited or hot materials could contact other combustibles. This problem is complex and controversial and will not really be settled without further analysis.

An interesting example of the type of sequence of events to analyze and the type of data needed about buildings in order to be able to predict secondary and tertiary fires is the Brighton, New York, gas fire and explosion catastrophe of September 21, 1951, reported by the National Board of Fire Underwriters.[17] An initial explosion (unknown origin) damaged a gas-regulator system in an underground vault, and as a result, regulators opened wide and allowed high-pressure gas to pass into a system designed to operate at a low pressure only. This overloading of the system resulted in numerous gas leaks in buildings and malfunctioning of gas appliances. Within a few minutes, a series of explosions and fires took place in the affected area. The high-pressure gas caused burners and pilot lights in operation to roar up to a height of 2 ft.

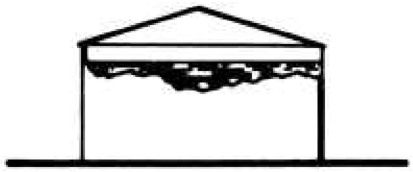
In some cases, burners lighted even though the gas was off. In other cases, the pressure surge extinguished pilot lights, which allowed the gas to escape. Gas meters designed for only a few pounds pressure failed. The splintered debris caused by the numerous explosions caught fire. Nineteen homes were completely destroyed; 25 additional buildings had serious damage. Gosland[18] has shown that there is a significant increase in fire susceptibility with the age of the installation. The subject of fires from causes other than radiation may be found in thermal radiation, Appendix E.

A.5.3 Other Enclosed Fixed Structures of High Fuel Value

Enclosed fixed structures with high fuel value, other than buildings, include storage tanks for liquid and gaseous fuels and other stationary enclosures, such as large wooden boxes containing high fuel loads. Reference 9 classifies large storage tanks for liquid and gaseous fuels as shown in Fig. A.7. Reference 9 (NFPA Nos. 58 and 59) contains further descriptions of L.P. gas-storage facilities. Small quantities of gases shipped about in ICC (Interstate Commerce Commission) cylinders and the various types of domestic L.P. gas ICC cylinder storage systems are often found in exterior fixed locations. Large liquid-fuel storage-tank areas are often "diked" with either dirt or concrete. The sizes of typical underground liquid-fuel tanks range from 3 ft dia x 6 ft length (300-gal capacity) to 10 ft dia x 17 ft length (10,000-gal). Typical sizes of aboveground liquid-fuel storage tanks range from 15 ft dia x 16 ft ht (21,210 gal) to 200 ft dia x 48 ft ht (11,281,200 gal). Gaseous-fuel storage, such as anesthetic gases stored in hospitals, are considered as part of the contents of the building.

Exteriorly stored crates with high fuel loads may include those containing explosives. Chemical plants usually store large quantities of potential fuel, such as sulfur and oxidizing materials like the chromates, dichromates, nitrates, and peroxides. By including munitions storage in this class, we bring up the question of whether explosives in a box are "enclosed." For our purpose, we will assume that they are and that if an explosive burns within its container, it will burn as if enclosed, and if it explodes, it will disrupt its enclosure and burn as if in the open. Explosives are an exceptional item and the definition of enclosure must be stretched to include these.

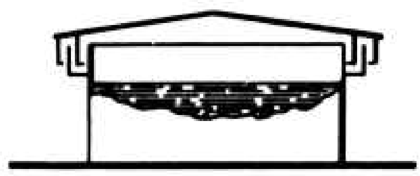
Because of the physical nature of liquid and gaseous fuels, they can be described according to the shape of their containers. Liquid-fuel storage tanks are usually sealed from the atmosphere or designed to change enclosure volume with increase of fuel volume with temperature. The vapor volume in the space above liquid fuels is important in specifying the pressure at which liquid fuels are stored.



ORDINARY CONE ROOF TANK

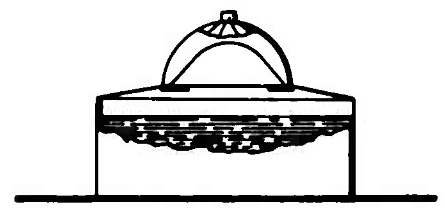
FLOATING ROOF TANK

Roof deck moves with liquid level



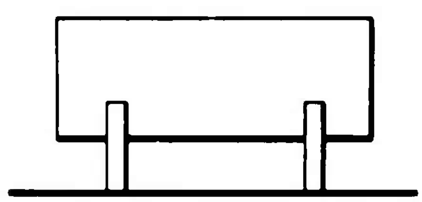
LIFTER ROOF TANK

Liquid-sealed roof moves up and down with vapor-volume changes

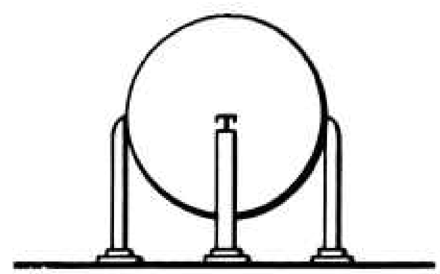


VAPORDOME ROOF TANK

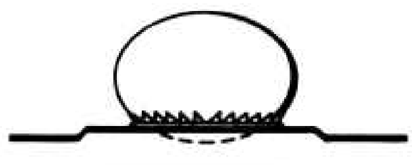
Flexible diaphragm in hemispherical roof moves with vapor-volume changes



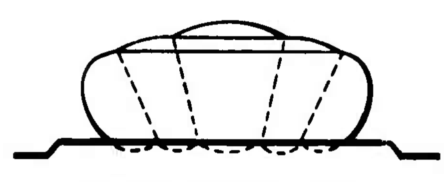
HORIZONTAL TANK



SPHERICAL TANK



SPHEROID TANK



NODED SPHEROID TANK

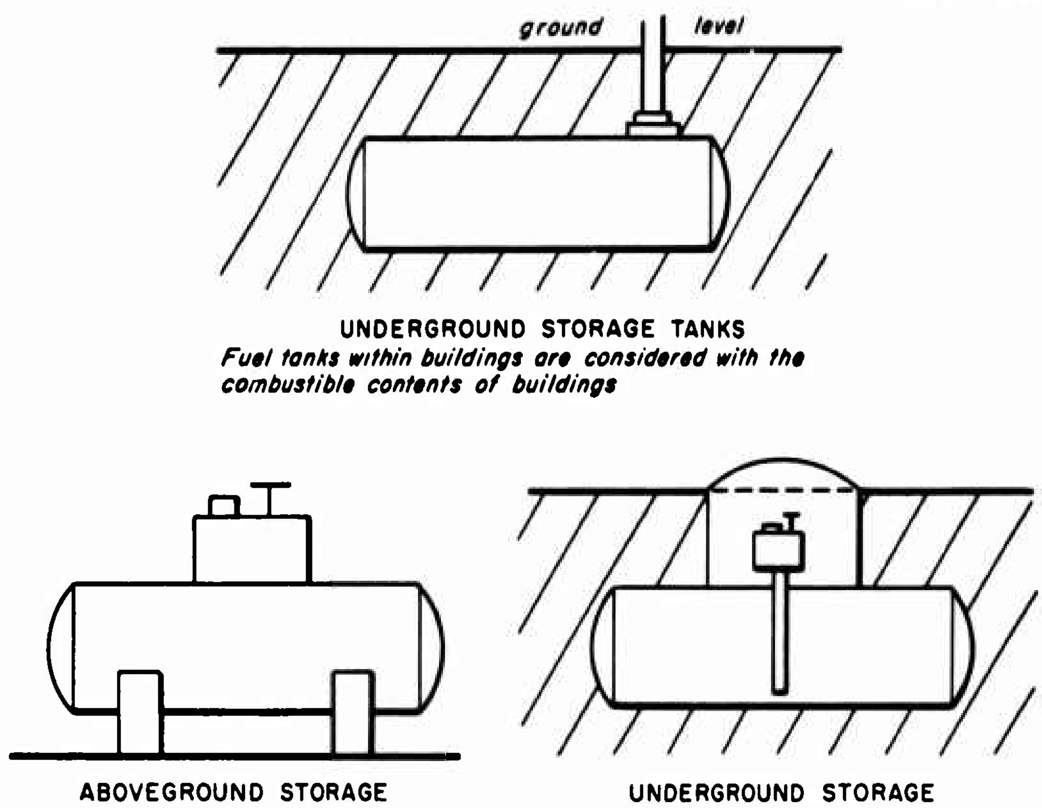


Fig. A.7 Classification of Large Liquid Storage Tanks[9]

These structures can be described by knowledge of the specification of typical containers, their fuel loading (number of gallons of fuel), burst features of the container (will stand how much heat?), dimensions of the container, distance off the ground, shape of the container above the ground, resistance of the structure to blast and debris, the container's location relative to other similar enclosures and to buildings (exterior or interior), the local topography, the fire value of the type of fuel stored in the container, and the arrangement of the container relative to location in the city. Large quantities of high-energy fuels are usually stored away from vital centers, since location is regulated by various zoning and storage codes.

The density of structures other than buildings is much less than building densities for an urban area; however, if one were to examine the density of these structures in, say, an oil-tank "farm" the density of fuel-storage tanks would be relatively quite high for such local areas. Reference 19 reports test experiences of Operation PLUMBBOB and two chemical explosions of ships that were used to predict the vulnerability of large oil tanks.

Reference 20 describes typical small commercial LP gas installations and an 18,000-gal bulk storage plant and cylinder-filling building. This report states the specifications required to describe the above installations and where specifications for similar types may be found, such as Section VIII, ASME Boiler Code, American Society of Mechanical Engineers, New York, N.Y. and the Interstate Commerce Commission Regulations (published by Agent H. A. Campbell's Tariff No. 9, Association of American Railroads, 40 Vesey Street, New York 7, N.Y.).

The same principles with regard to describing secondary and tertiary fire locations in buildings apply to these structures with one important difference: since rupture of the fuel tank is required, in most cases, for a fire to occur, the effect of blast upon fuel tanks can be estimated by specifying the psi level necessary to rupture the tank.

A.5.4 Enclosed Fixed Structures With Low Fuel Value

These structures include either empty tanks and other enclosures of low fuel value or non-fuel tanks or non-fuel enclosures with non-fuel contents. Examples of these are water tanks, compressed air tanks, liquid N_2 (nitrogen) and inert-gas storage tanks, and fixed empty tanks of all sorts. Usually, whether a tank is full or empty must be determined by onsite inspection, although by prior knowledge and calculation this information can sometimes be ascertained from observation of an urban area over a period of time. Specifications of these structures are similar to the fuel tanks discussed above.

A.5.5 Enclosed Transient Structures

Let us now examine the transient enclosed fuels, such as the vehicles of transportation and others that are either transported by human activity or moved from place to place by the wind. The highest fuel loads in this class occur in rail cars or trucks that are transporting flammable liquids or gases. These are found moving along the outskirts or through an urban area or parked near structures (gasoline stations, factories, etc.,). These are few in number and represent local conditions only. Automobiles, however, can be found on most urban streets and in parking lots arranged in various patterns.

For a city like San Francisco, where the density of automobiles is high, most streets can be expected to have parked cars along both sides of the street at any time during the day or night. Automobiles have gasoline tanks, upholstery, car seats and cushions, oil in the crankcase, rubber tires, etc., that can burn. Sedan cars most generally are surrounded by a steel shell that encloses the interior, and the ventilation a fire would receive would depend on the degree of window and door openings, etc. Ignition tests of cotton upholstery and stuffing of automobiles during Tumbler-Snapper nuclear weapon tests in Nevada at Operation UPSHOT-KNOTHOLE,[21] showed that fires may smolder for hours after exposure to thermal radiation, that the build-up of fires is a slow process, and that spread from car to car is rare, which agrees with actual automobile fire-loss experience.

The larger vehicles of transportation, such as railroad tank cars, tankers, and loaded grain ships, may have huge fire loads. Many rail cars and ships have very low fuel values when they are empty in that they are usually made of steel with very few wooden structural parts and, hence, can be described in terms of their contents only.

A.5.6 Open Fixed Structures of High Fuel Value

The open fixed structures in an urban area are numerous and have substantial fuel loadings in local areas. Many of these are made of wood. Wooden bridges are found in local areas, but are not numerous. Utility poles have usually been made of wood, but they are being replaced in some places with the longer lasting, easier to maintain aluminum or steel poles. Wooden fences usually occur only where the building density is quite low (such as residential areas), and are often attached to buildings. An important parameter is the ability of a fence to resist wind. Those with large gaps allow the wind to blow freely and do not tend to accumulate windblown fine vegetative fuels or litter. Certain places of assembly, such as grandstands, are attached to buildings or are entirely in the open. Information regarding the fuel loading of this class of structure is best obtained by spot surveys.

A.5.7 Open Fixed Structures of Low Fuel Value

Open fixed structures of low fuel value for the most part do not burn, for example, concrete roads and freeways. However, asphalt roads and railroad right of ways (vegetative fuels, wooden railroad ties, etc.,) may burn. The most important reason for describing these parameters is that they are firebreaks. Most of these structures are at ground level; however, steel bridges, elevated freeways, etc., can be an important factor in altering the wind profile in local areas of a city. These structures can be broadly classed as either (1) local structures that separate a few high-fuel-load structures, or (2) linear structures that divide a city into various fire districts. The pattern, composition, and widths of city streets and roads are readily obtainable from city planning maps.

A.5.8 Open Transient Structures

Open structures that are transient comprise litter, such as newspaper, and certain combustible goods shipped by the modes of transportation. Cotton bales on a pier are an example of an item that is transient in that it is not stored outdoors for long (depends on the weather) and will probably burn as if in the open. Garbage dumps are fixed but the garbage trucks are consistently on the move. The component of open transient structural fuel consists of low-fuel wrappers and litter; the nonburnable component of garbage. The description of structural trash in an urban area must indicate (1) degree of subdivision, (2) type of fuel, (3) amount of the fuel in a given area, and (4) relation of the fuel to buildings, tanks, fences and the other susceptible structures. There is a trend from paper wrappers (high fuel value) to aluminum, plastic, etc., (low fuel value), but it is doubtful whether this trend is significant enough except for local city areas to alter the desired description of litter and goods.

A.6 VEGETATION

A.6.1 General

Vegetative fuels are important to urban fire vulnerability in two major ways: (1) shielding of combustible materials from weapon thermal radiation and fire radiant heat, and (2) either enhancing or hindering fire spread. The numerous parameters required to properly explain the role of vegetative fuels to urban fire vulnerability may be placed into either or both of the above groups. The importance of vegetative fuels to urban fire vulnerability is evident from urban peacetime conflagrations known to have started in vegetative fuels (Berkeley in 1923, Bel-Air in 1961).

In heavily built-up urban areas, there are few places that are naturally vegetated. Parks and plantings along streets and around lakes are generally the only places where vegetation may be found. The vegetation is usually well maintained and consists mainly of trees, grass, weeds, and/or shrubs. When we examine less densely built-up areas (as we move away from the downtown area), we notice more land in, or available for, plantings and also the proximity of "natural" wildland fuels (Long Island is an exception) to the urban area. A wide range of relationships of adjacency to urban structures is exhibited at all locations, from direct contact to large separation by vacant land. Vegetative fuels are arranged (landscaping) about urban structures in patterns that may be described as parameters of the "homogeneous" subarea of a city. Whereas brush is virtually absent from parks and sides of streets in downtown subareas, accumulations of medium-sized sticks, branches, and brush exist in non-downtown subareas (especially in areas of low maintenance, along railroad right-of-ways, and between houses). All vegetative fuels are in the open and will burn with the characteristics of fires in the open (see App. F for these characteristics).

Vegetative fuels in any location are described according to weight (heavy, medium, or light)(discussed subsequently), and interaction (adjacency) with urban structures. The weight of vegetative fuels is related to fuel size and subdivision in most cases: 1. heavy: smallest number of vegetative individuals (plants) and largest weight per unit area per individual; 2. medium: moderate number of individuals and moderate weight per unit area per individual; and 3. light: largest number of individuals and smallest weight per unit area per individual. We will use each of the terms heavy, mdeium, and light vegetative fuels to refer to the average weight per unit area of a plot of vegetation containing many individuals.

The general nature of vegetative fires, whether it be a ground surface, or forest fire, can be related to the weight of the burning vegetative fuels. Ground fires occur in accumulations of organic matter and smolder for long periods of time. Ground fires can occur even when the fuels are moist because they spread slowly, and moist fuels in the fire front will dry out (also, ground fuels [such as duff] are seldom uniformly moist throughout their profiles). Surface fires occur in litter, herbs, and shrubs and are characterized by rapid fire spread. Forest fires occur in dense, woody areas and generally everything from the ground up is burned.

Heavy-and medium-weight vegetative fuels are considered fixed in location prior to burst, and light-weight vegetative fuels are considered to have potentially transient locations (wind distributed, high level of maintenance, etc.,) prior to burst. Of course, after the passage of the blast wave, any of these fuels may be displaced. Certain of the blast effects on specific vegetative fuels are discussed subsequently. The distribution of vegetative fuels due to blast or fire-induced winds is rather unpredictable.

All vegetation varies with altitude, season, and growing conditions (weather, soil, etc.), and the overall influence of these for our purposes may be best expressed in terms of the days of peak fire danger over rather large areas of the United States.

A.6.2 Heavy Vegetative Fuels: Fixed and in the Open

Trees compose the majority of this class of vegetative fuels. Parameters are their height, opaqueness to thermal radiation and radiant heat (% transmissivity of leaf cover and structural framework), and location with relation to other types of combustible materials and to openings. Trees are expected to be essentially the only class of vegetative fuels tall enough to shield openings, exterior or interior combustibles, and roofs as high as the fourth floor of multistory buildings from the thermal radiation of a nuclear explosion. Table A.6 (from Ref. 23) shows an example of the variation in dependence of the brightness in a stand of timber on the development of the vegetation and the character of the stand (70 years old near Zurich, Switzerland).

TABLE A.6

Brightness* in Timber Stand in Percent of That Above Open Land

Time of Measurement	Coniferous Trees (A)	Mixed Trees (B)	Deciduous Trees (C)
End of April before leafing out	8	22	51
End of May after leafing out	7	14	23
End of September before changes of color	4	4	5

(A) Pure spruce.
(B) 55% spruce, 36% beeches, and 9% other deciduous trees.
(C) 73% beeches, 22% ash, and 5% other deciduous trees.

It is anticipated that shielding by trees of urban combustibles can be described in terms of the species of tree, its branching characteristics (length of trunk included), height, proximity to combustibles, whether deciduous or coniferous, month of the year, climate, age, orientation of leaves (position of sun), and the angle of the direct line of sight from the tree to the fireball.

* Brightness refers to readings made on the ground with an exposure meter.

The shielding properties of broad-leaved trees against thermal radiation have also been studied. Bruce and Downs[2] measured the transmission of light through each of 35 large elm, maple, oak, cottonwood, and oak trees without leaves (to simulate a deciduous tree in winter) with a photographic exposure meter; however, the details of how the experiment was performed are not included. The average transmission was found to vary from 65% just above the main crotch to about 80% through the upper part of the crown.

Leaves transmit about 10% of the light ($< 0.7\mu$ wavelength), or 50% of the light ($> 0.7\mu$ wavelength)[23] (Fig. 121, p. 274) impinging on them so that most light that penetrates foliage passes between the leaves and the supporting framework (trunk and branches, which can be assumed to be opaque).

Nakamura[24] has experimentally studied the effectiveness of evergreen trees (conifers) in blocking the radiant heat from fires, in particular the extent to which radiant heat is transmitted from building fires to nearby structures. The "shape" of the tree and the shape of the flaming surface are cited as parameters. He concludes that the heat shielding power of fairly densely foliated trees is high.

Fons et al.[25] have studied the resistance of trees to blast and have developed a model that requires information on stem form, natural period, and the internal dampening of the stem. Trees will be uprooted and displaced depending on the peak overpressure level received. Trees are sources of the largest firebrands, in wildland areas, and of much of the light-and medium-weight vegetative fuels on the ground in the form of needles, leaves, broken branches (large and small), and organic accumulations.

A.6.3 Medium Vegetative Fuels: Fixed and in the Open

Medium vegetative fuels include the lighter-than-average heavy fuels and the heavier-than-average light fuels. The shielding effect of medium vegetative fuels is not as great as that of trees, but may be considerable for certain species. This type of vegetative fuel consists of medium-sized herbs and shrubs and the medium-sized fallen limbs of trees, which may be considered relatively fixed even in the stronger wind velocities. The U.S. Forest Service has estimated that medium-weight vegetative fuels in natural environment contain about 25 to 40 tons of fuel/acre.[3] These fuels are most significant in the shielding of openings in the first floor of buildings and in the formation of intermediate-size firebrands.

A.6.4 Light Vegetative Fuels: Fixed or Transient and in the Open

Light vegetative fuels are the products of trees, bushes, and herbs (such as grass and weeds), loose or attached to the ground. Leaves, needles, and some vegetative debris are included here. Organic accumulations occur in all vegetated locations and most often are quickly degraded. Organic litter comprises freshly detached light fuels, whereas duff comprises light fuels in an advanced state of decay. They are found lying on the surface of the ground, scattered among the heavy and medium vegetative fuels. The amount of these fuels at a given location depends on the level of maintenance (for example: downtown subarea--high level of maintenance; wildlands--low level of maintenance), the season of the year, and the major type of vegetation there. If the maintenance level is high, these fuels are disposed of by burning or as garbage. However, if there is little maintenance, the distribution of light vegetative fuels is determined primarily by weather factors, particularly wind and precipitation. Light fuels are found piled against obstacles to the wind, such as sides of buildings, fences and stairways, and sides of hills.

These fuels are the most readily ignited of the vegetative fuels under comparable conditions. Light fuels, in general, form small and relatively short-lived firebrands; i.e., sparks. The shielding effect of light vegetative fuels from thermal radiation and radiant heat is quite insignificant because they are low in height, and hence, such fuels are primarily significant in enhancing (or hindering) firespread.

A.6.5 Sources of Data on Vegetation

The nature of the descriptive data required in assessing the role of vegetative fuels in urban fire vulnerability depends a great deal on the intended use of the data. National phytogeographic maps are available, such as Marschner, F.J., Major Land Uses in the U.S.,[27] that indicate croplands, climatic zones, and hardwood and coniferous forests. Data on vegetation is often too far out of date to be useful, or of such broad coverage that cities are dwarfed in comparison to the size of the map. For the most U.S. cities of 25,000 or more population, the available land-use maps[28] have a scale of 1000 ft/inch and provide adequate information for fire assessment in urban areas. The U.S. Forest Service has studied fire effects in vegetative fuels for a number of years, and their soil-vegetation and timber-type maps are useful sources.

The best sources of data are the aerial photographs and spot surveys of individual cities. The percent of ground covered by each of the types of vegetative fuels can be determined for any urban subarea (or for any arbitrary division). Generally, this figure will be greater than 100% for a heavily naturally vegetated area (due to overlap of various types of vegetation) and much less than 100% for any urban vegetative plots because of their high level of maintenance. Any survey

of an urban area should include the location of "fuel paths" (specific locations where vegetative fuels are continuous with urban structures and hence have a higher probability of spreading fire to the structure). Examples are trees planted as a windbreak in line with a house, and grass (or other fine fuels) which is susceptible to ignition and is located so that brush (medium-weight) and then trees would catch on fire.

A.7 METEOROLOGY

A.7.1 Meteorological Parameters

Meteorological parameters enter into almost every step of a fire vulnerability analysis of urban areas--from the effect of clouds on the transmission of thermal radiation to the effect of precipitation on the termination of fires. Hence, we confine discussion here to describing those meteorological elements that have direct bearing on the condition of urban fuels or the movement of a fire (spread and regression) in a city. The meteorological elements that pertain primarily to atmospheric transmission (clouds in particular) are discussed in Appendix C (Atmospheric Transmission).

Six weather elements recognized by meteorologists can be considered as target parameters:

Atmospheric pressure	Temperature
Humidity	Winds
Precipitation	Ground Fog

Each of these can be shown to have various degrees of effect on fuel condition, fire spread, or fire termination. It will be important for us to specify the location and size of the urban area to which the description of each of these elements applies.

Overall urban weather patterns of atmospheric pressure, temperature, humidity, winds, snow cover, rainfall, and ground fog depend on averages of a large number of observations from different areas of a city or region. Each of these observations describes a particular weather element for the immediate area of the observation, and the reliability of the observation will vary as one attempts to extrapolate a single observation to the surroundings.

Weather data concerning urban areas is regularly recorded by the U. S. Weather Bureau at thousands of weather observation stations. These data are probably adequate for national fire-vulnerability analyses, using gross overall weather patterns, and are also useful in forecasting the weather for an urban area. Often, certain local urban observations are quite different from those reported by the Weather Bureau stations. However, additional weather measurements are taken regularly by many

other organizations for a variety of purposes. Hence, the meteorology of an urban target area can probably be adequately described by the use of existing reported weather data.

Some elements are much more sensitive to distance from the point of measurement than others. For instance, the temperature in a city is usually reported from a centrally located weather-reporting station and from several outlying airport weather stations. The differences among the temperatures reported by these stations will probably be quite small most of the time, although instances of large fluctuation are possible. On the other hand, if we were to compare data on wind speed and direction at these reporting stations, the chances are that they would show quite large variations of these wind parameters with time. However, since we are not concerned with describing the methods of weather forecasting but with describing those weather elements that are necessary for analyzing urban fire vulnerability, let us begin by considering the atmospheric pressure of an urban area.

A.7.2 Atmospheric Pressure

We may consider the atmospheric pressure of the air over a city (exterior to structures) to be practically uniform. The pressure within an enclosure will depend on the rate of atmospheric-pressure change and/or the size of the openings into an enclosure. We can assume that the pressure throughout a room in a building may be described by the atmospheric pressure measured at the local weather-reporting station. The U.S. mean-sea-level pressure in millibars for the month of January is 1017 to 1020; for July, it is 1011 to 1017.[29] Atmospheric pressure shows regular diurnal variations caused by the alternate daytime heating and nighttime cooling of the earth's atmosphere.

The atmospheric pressure at a specific location varies from hour to hour and from day to day due to the passage of large-scale pressure systems: "Highs" and "Lows." These irregular pressure variations are most pronounced in the middle latitudes (such as the U.S.) where storm activity is at a maximum compared with the tropics for which pressure charts show few fluctuations except during tropical storms. Constant-level charts refer to pressures reported by all stations for the same elevation; whereas constant-pressure charts are constructed for various surfaces of uniform pressure (basic information needed is the elevation of the constant-pressure surface being studied). Rapid, large changes in atmospheric pressure often occur during storm conditions. (Several of the weather elements reach their greatest intensity in thunderstorms except for a few extreme weather phenomena; that is, rain falls at a rapid rate, wind gusts can be greater than 75 mph, and hailstones may fall.) It is of interest here that a component of the force of a wind is the pressure-gradient force defined as:*

*Ref. 29, p. 125.

$$\frac{1}{\rho}\left(\frac{dp}{dn}\right) \qquad \text{(A.1)}$$

where ρ is air density, and $\frac{dp}{dn}$ is rate of pressure change with distance.

Atmospheric pressure charts may be used to estimate pressure-gradient forces and hence the speed and direction of the wind. The isobars of a constant-level map or the contours of a constant-pressure chart may be used to read wind speeds (assuming only pressure gradient and Coriolis forces; no acceleration or frictional forces) directly. In general, pressure is high in the winter over the U.S. land mass and high in the summer over the oceans. Over the coasts, intermediate types of variation are found.

Atmospheric pressure varies with altitude, because of the decrease in air density with increased altitude. A fundamental equation useful to meteorologists, and perhaps to fire analysts, is the following, which is derived from the general gas law:*

$$\ln p_o - \ln p = \frac{gz}{RT} \qquad \text{(A.2)}$$

where

T = Kelvin temperature
R = 2.87×10^6 (ergs/°K-gm)
$g \cong 980$ cm/sec^2
z = altitude in cm
p = pressure (dynes/cm^2) at z.
p_o = pressure at sea level (dynes/cm^2).

which is the relationship between pressure, temperature, and altitude. For our purposes, we can see from this equation that the pressure change from the first floor of a 1000-ft building to the top floor (assuming a constant temperature of 25°C over the height of the building and standard pressure, 760 mm Hg or 1013.25 millibars, at the base of the building) is about 26.8 mm of Hg. From this, it can be assumed that for even the tallest urban structure there is a small variation in atmospheric pressure with height within an urban area. High-elevation cities, such as Denver (about a mile high), exhibit greater reductions in atmospheric pressure from that at sea level, than height differences exhibited in a single urban area (such as from the first floor to top floor).

* Ref. 29, p. 109.

A.7.3 Temperature

The temperature of an urban area determines the amount of moisture the air about a city is capable of holding before precipitation occurs. Exposed surfaces of a city are warmed by absorbed solar radiant energy (incoming) some of which is radiated back (outgoing) into the atmosphere. The factors that are important in affecting and describing temperature of a locality are:

1. Latitude (most important)
2. Distribution of land and water
3. Topography of the locality.

Cities in the U.S. (middle-latitude temperate zones) exhibit an average daily ground-surface variation in temperature, as shown in Fig. A.8 which indicates the lag in cooling from insolation.

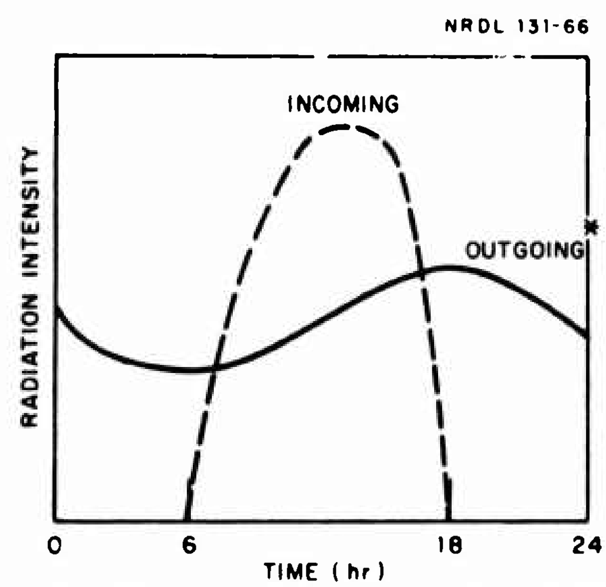


Fig. A.8 Example of Daily Temperature Variation for Typical Middle-Latitude City

(Ref. 29, p.92)

Besides the daily variation in temperature, cities exhibit an annual fluctuation of temperature, such as illustrated in Fig. A.9 by three example cities. The smallest annual temperature ranges occur nearest the equator (low latitudes) and the largest occur in the highest latitudes, but location within a continent also can have an effect, as shown in Fig. A.9.

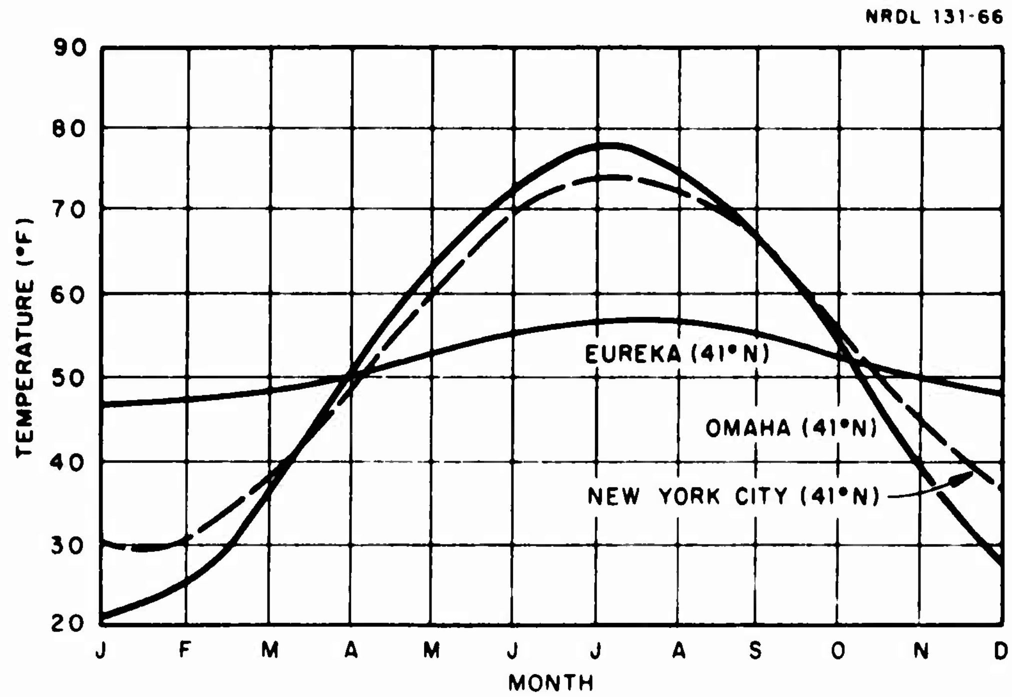


Fig. A.9 Example of Annual Temperature Fluctuation in Cities (Ref. 29 p. 92)

The temperatures within the enclosures of an urban area are generally considered separately from those commonly reported at weather-reporting stations and are discussed in A.8.5 with the description of the ambient conditions of fuels. This separate consideration is necessary because of the heating and cooling systems in buildings and the covers over openings, which maintain artificial meteorological conditions. Urban structures are generally arranged in such a way in the U.S. that the northern exposure of buildings, etc., will receive less solar radiation than the southern exposure. Specific locations of an urban area (such as alleys in downtown areas, vegetative canopy, etc.) may receive little, if any, solar radiation due to shielding by structures or vegetation.

A.7.4 Humidity

The relative humidity of the air is a useful parameter to estimate whether certain ground features influence the precipitation occurring in an urban area or in its vicinity. Very moist air contains up to 4% water by volume, and the moisture is one of the most important constituents of the air of concern to meteorologists. This moisture comes from oceans, lakes, rivers, wet soil, vegetation, and snow or ice fields. Taylor* has concluded that the moisture of the air is altered by parks, reservoirs, lakes, etc., of small size, but that in order to alter precipitation in the vicinity of the body of water it must be greater than 10,000 square miles in surface area (for example, Lake Erie).

The air in the U.S. practically always contains moisture and whether rain or snow falls depends on meteorological conditions. We will assume here that moisture over the exterior of urban structures can be predicted on the basis of the amount and type of precipitation, duration of precipitation, and the time since the last significant precipitation. When no precipitation occurs for a long period of time, exterior fuels can be expected to be in equilibrium with the moisture content of the air.

The temperature at which the relative humidity is 100% is called the dew point. At this temperature the common weather processes remain relatively unaltered. It is also known that fuels in an urban area do not generally have time to achieve equilibrium with the moisture content of the air in the presence of winds whose speed and direction are rapidly changing due to unstable conditions of the atmosphere. The forecasting of the temperature in an urban area depends a great deal on knowledge of this moisture content.

A.7.5 Winds

Winds over an urban area are influenced by

1. Arrangement of structures.
2. Height of structures.
3. "Density" of structures.
4. Distance between structures.
5. Size of structures.
    a. Buildings: dimensions (length, width and height).
    b. Nonbuildings: shape: spherical or cylindrical tank, steel towers, etc.
6. Arrangement, abruptness and elevation of ground-surface topography.

* Ref. 29, p. 103.

7. Frictional forces of urban features.

8. Topography and meteorological conditions of the surrounding region.

9. Others.

As previously mentioned, winds that blow in a straight line, with no acceleration or frictional forces acting upon them, have speeds proportional to the pressure gradient and may be read directly from weather charts that indicate constant isobar pressure intervals (in this case speed is inversely proportional to the isobar spacing). The wind speed (assuming no acceleration or frictional forces) in the U.S. is also inversely proportional to the sine of the latitude and inversely proportional to air density.* Because of the relatively small size of urban areas, it can be assumed that the Coriolis forces will not come into play; however, frictional forces will deflect winds.

The circulation of air in an urban area is due primarily to the overall wind pattern of the region, the alteration of winds due to urban features and local thermal circulations. The general atmospheric circulation of the U.S. moves from east to west in a series of "Highs" and "Lows." The height of wind measurements must be specified for a detailed analysis. A knowledge of the winds-aloft pattern may be useful in predicting and analyzing wind patterns in a city and in explaining some of the more massive fire phenomena. Wind direction may have significant influence on wind speed in those cities where topography, structures, and/or vegetation are oriented to allow free passage in one direction but block the wind in some other directions. Bernoulli and Venturi-like forces will tend to increase the wind speed between narrowly separated obstacles. Examples of this are narrow streets in a built-up area or the canyons, such as the Santa Ana Canyon outside of Los Angeles.

To describe in detail the speed and direction of winds in a city, an accurate analysis of the wind field must be made. Valuable information on the wind field can be obtained by the techniques of streamline analysis.** The technique presents a detailed picture of the distribution of wind speed and direction at the level being studied. A disadvantage of the technique is that it does not lend itself to differential analysis by which it is possible to build from one level to another. Completed streamline charts conveniently present many features of interest concerning the wind, such as the lines of convergence and divergence, vortices, neutral points, and areas of high and low wind speed.

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* Ref. 29, p. 126.

** Ref. 29, p. 137.

Rotation of air in an urban area may be started where the surface wind is retarded by the topography, structures, and/or vegetation, and where there are local thermal sources. Extreme wind rotation is found in dust devils, whirlwinds, waterspouts, tornadoes, and hurricanes. Hills are prolific thermal sources and are of special importance in the production of large clouds.[30] Valleys, on the other hand, tend to subdue the growth of cumulus clouds. Examination of the distribution and strength of thermal sources in an urban area may lead to a better understanding of the winds of these areas.

Surface winds are steady or frequently calm and are due to a condition of stability in which the vertical motion of the wind is suppressed primarily by the vertical distribution of the temperature in which overlying air is relatively warmer and lighter. Air is considered stable if there is no more than about 5°F change in temperature per 1000 ft change in altitude in dry air. Air in surface layers is usually stable during calm, clear nights and becomes unstable in midday as the ground is heated. Inversion layers (horizontal layer that increases in temperature with altitude) commonly occur in stable air. Inversions may occur above an urban area and vary a great deal in thickness.

Generally, local winds depend on turbulence, which is generally caused by either mechanical obstruction or thermal currents, and in some cases by the winds that have become rotational in direction. Sekine[31] has measured turbulence, vertical distribution of wind velocities, and horizontal wind velocity in Tokyo and has compared these measurements with similar experimental measurements on urban models. The roughness of buildings is described in these models by the height of buildings, distance between buildings, and size of buildings. Sekine[31] has shown that, when the thermal heating of the ground is not too conspicuous, the vertical distribution of average wind speeds near the ground can be represented by the logarithmic distribution:

$$U = \frac{U^*}{K} \ln \frac{z-d}{z_o} \qquad \text{(A.3)}$$

where

U = vertical distribution of wind velocities

U^* = friction velocity

$= \left(\frac{\tau}{\rho}\right)^{1/2}$

τ = shearing friction stress

K = Karman constant

$\cong 0.4$

z_o = roughness length (size of unevenness of the ground surface)

z = height above ground surface

d = zero plane displacement

The parameters that describe urban features with regard to turbulence are difficult to determine, since the effect of turbulent flow over various shapes is not known well enough to do this on a scale necessary for detailed analysis.

A.7.6 Precipitation

A description of precipitation in an urban area for the purposes of fire vulnerability can be broadly expressed as either snow on the ground (snow cover), rain, sleet or ice on the ground. The persistence of snow on the ground generally precludes the temperature of the air and/or the ground being in or above the range of the freezing point of water. Snow cover in U.S. cities depends on geographical location, altitude, and the necessary meteorological conditions for snowfall. Snow cover is a continuously varying quantity and may be described as the probability of snow of a certain depth at a specific U.S. location for each week of the year. Schroeder et al.[32] have prepared snow-cover probability maps from tabulations of snow cover and partial snow cover of 1-inch or more depth at the end of each 17 weeks by 1-degree squares over the U.S. The source of Schroeder's data is the "Depth of Snow on the Ground" maps of the U.S. Weather Bureau's Weekly Weather and Crop Bulletin. Maps are only available for the period December through March when the greatest area of the U.S. probably has snow cover. Probability maps for the early fall and late spring months would be desirable, but are not available at this time.

In urban areas, snow cover will partially be controlled by man's efforts in cleaning streets, parking lots, sidewalks, etc. Snow will remain on some types of roofs for longer periods than on others, and the depth of snow is quite variable with location. The albedo (reflectivity) of snow over an urban area should be described for calculating the effect of enhancing thermal radiation upon the target. In most cities, especially large industrial cities, the distinction between fresh and old snow can be used to predict the decrease in albedo due to the settling of dust and dirt upon new snow.

Rain on the ground is described as the amount of rain measured in an urban area within a specific period of time. Since a large amount of rain will run off the exteriors of structures, vegetation, etc., and be collected in drainage systems (sewers, etc.), the amount of rain is probably not as important as the length of time fuels are in contact with moisture. Urban areas, with few exceptions, are built so as to protect from the elements those areas of high fuel loads (building structural elements and contents), such as lumber and coal stored exteriorly and the exterior fuels. There is a trend for lumber to be stored under tarpaulins or shelters or indoors so that such exceptions are even more rarely found.

On the basis of the width of firebreak required to stop an urban fire ("no spread" conditions, See App. F), Chandler et al.[36] have proposed the following conditions of precipitation in an urban area that would prevent fire from spreading.

Light residential - 1-inch precipitation and "no spread" condition for 36 consecutive hours, or "no spread" condition for 48 consecutive hours without precipitation.

Heavy residential - 1.5-inch precipitation and "no spread" condition for 72 consecutive hours, or "no spread" condition for 100 consecutive hours without precipitation.

Commercial - 2.0-inch precipitation and "no spread" condition for 7 consecutive days, or "no spread" condition for 10 consecutive days without precipitation.

City center and Massive Manufacturing - 2.0-inch precipitation and "no spread" condition for 2 consecutive months, or "no spread" condition for 3 consecutive months without precipitation.

A.7.7 Ground Fog

Clouds in general are considered atmospheric-attenuation parameters and are discussed in Appendix C. However, one form of cloud, fog, which is actually a cloud on the ground, will be considered as a target parameter. Fogs form in several ways:

1. Ambient air cools to its dewpoint (air-mass fogs).
2. Moisture of air increases to saturation point (frontal fogs).
3. Mixing of two parcels of air.

Willet[33] introduced a fog classification system in 1928, which was later (1959) modified by Byers. Most air-mass-fog data can be grouped into two broad categories: advection or radiation fog. Advection fogs commonly occur in coastal cities and are those types in which cooling is caused primarily by the transport of warm air over a cold surface, whereas radiation fogs, which commonly occur inland, are those fogs in which radiation constitutes the principal cooling mechanism. A summary of fog types and classification useful for describing urban-area fogs after Willet and Byers is given in App. C.

A.7.8 Average Dates of Peak Fire Danger in U. S.

Studies of the times of the year of the fire season of a particular region based on rainfall, relative humidity, and temperature have produced average dates that describe the fire season on a national basis. October 15 may be taken as the date of peak fire danger for most of the U.S. (areas excluded are the Pacific Northwest and northernmost regions of the U.S., whose dates of peak fire danger come before October 15).*

A.8 DESCRIPTION OF FUELS IN URBAN AREAS

A.8.1 General

One of the most important parameters concerning an urban target with regard to fire vulnerability is the description of fuels. For our purposes, we define a fuel as any substance that has the potential of supplying heat or power to a fire of any size. Fuels may be completely described for these purposes by knowing:

1. The type or kind of fuel.
2. The distribution of each type of fuel.
3. The fields of view of each type of fuel.
4. The ambient conditions of each type of fuel.
5. The variations in 1, 2, 3, and 4, with the time of day, week, or year.
6. The variations in 1, 2, 3, and 4, with location (local and nationwide).
7. The variations in 1, 2, 3, and 4 caused by post-nuclear-burst events and related conditions.

A.8.2 Type of Fuel

A variety of classification schemes may be used to describe the fuels by type. All fuels may be classified according to their basic physico-chemical properties, such as physical state (solid, gas, or liquid), density, goemetry, state of subdivision, heat of combustion, flammability, chemical composition, melting point, and several others. Fuels are also often classified according to a particular response. For example, kindling fuels are those fuels capable of glowing or flaming from the thermal radiation of a nuclear burst, and fire-resistant fuels are those relatively unaffected by fire for a specified length of time. Each of these schemes of classifying fuels is useful to some extent in understanding the multifaceted phenomena associated with urban fires. Let us now examine a few of these in more detail.

* Ref. 4, p. 28, Fig. 6.

The most general division of fuels is according to their physical states. Solid fuels are by far the most abundant urban fuels based on weight and they would constitute almost the entire urban fuel load at the time of burst. The most abundant of the solid fuels are those with a cellulose base, like wood, wood products (for example, paper), and nonwood cellulose (for instance, cotton and cotton fabrics). Noncellulose-base solid fuels may be grouped according to the following examples:

1. Coal.

2. Protein-base fuels: wool, hair, and leather.

3. Solid synthetics: plastics like bakelite, cellulose acetate, lucite, nylon, plexiglas, polyethylene, teflon, and others.

4. Rubber and its products.

5. Solid chemicals: sulphur, others.

6. Solid chemical products: hardened paint, explosives, others.

The physical state of some fuels is temperature dependent; the physical state of other fuels is not clear-cut, such as certain resins, greases, and glasses, which are actually liquids of great viscosity. Also many of the fuels, like wood, found in urban areas will contain gaseous and/or liquid fuels (to various extents) that may be released due to post-burst time events.

Gaseous fuels found in urban areas are typically either flammable or capable of contributing to a fire, even though the substance (for example, oxygen gas) does not itself burn. Flammable gases are the most abundant and generally are of petroleum base. Some of the flammable gases commonly used as fuel are natural gas, manufactured gas, liquified petroleum gases (butane, propane, etc.), acetylene, and hydrogen. Non-fuel gases, such as nitrogen (N_2), argon (A), helium (He), carbon dioxide (CO_2), sulphur dioxide (SO_2) and various fluorocarbons that are used in aerosol pressure cans, etc., may be important locally in spreading fires if burst events and subsequent events result in the bursting of their containers.

Due to the advent of the rocket engine and for other reasons, certain nonpetroleum liquid and gaseous fuels, such as cryogenic oxygen and hydrogen, may be found stored locally and transported in and about some urban areas. Other nonfuel and fuel chemical liquids with high vapor pressure at ambient temperatures should be included here, since they are also found in urban areas in small to large quantities.

Liquids are distinguished from gases arbitrarily according to the National Fire Protection Association (NFPA) No. 30 Flammable Liquids Code as having vapor pressures not exceeding 40 psia at 100°F. Flammable liquids are those having a closed-cup flashpoint below 200°F. According to National Fire Protection Association No. 30, these liquids may be

classified as follows:[9]

Class

I. Liquids with flashpoints $\leq$ 20°F.

II. Liquids with flashpoints > 20°F. $\leq$ 70°F.

III. Liquids with flashpoints > 70°F. < 200°F.

(Those liquids with a flashpoint $\bar{>}$ 200°F. are referred to as combustible liquids.) One method for grading liquids according to their flammability is as follows:

Flammability Class	Relative Hazard
Ether	100
Gasoline	90-100
Ethyl Alcohol	60-70
Kerosene	30-40
Paraffin Oil	10-20

Another method of classifying all fuels is by their potential of contributing heat to a fire, or heat of combustion (caloric value). The heat of combustion refers to the complete burning of the fuel. It represents maximum heat released by complete oxidation of an amount of fuel. A representative list of heats of combustion of urban fuels is given in Table A.7.

Other descriptive properties of fuels that can be used in typing fuels include the surface-to-volume ratio of a fuel, whether the fuel is light or heavy, and whether the fuel is urban or wildland. The surface-to-volume ratio is directly related to the state of subdivision of a fuel and is a useful parameter in describing fundamental fire processes (for further discussion see App. D). The separation of fuels into light or heavy is made on the basis of a fuel's density. Wildland fuels are trees, grass, brush, other plants, and plant products (needles, leaves, punky wood, etc.) which are normally found contiguous with urban areas. Usually, this type of vegetative fuel found within an urban area is not spoken of as wildland, even though the type of fuel is about the same (see A.6); hence, the distinction between vegetative wildland and urban fuels is primarily one of location.

Urban fuels of a specific type may be classified according to the use or function that these fuels may be expected to serve. For example, Table A.8 gives the possible uses of some cellulosic-base fuels that may be found in cities.

TABLE A.7

Heats of Combustion of Some Urban Fuels[9]

Fuel	Heat of Combustion (approximate*) Btu/lb
Petroleum Products:	
crude and fuel oil	
gasoline	
kerosene	
coal tar oil	17,000-20,000
gas oil	
asphalt	
paraffin	
pitch	
Coal:	
anthracite	
semi-anthracite	8,000-14,800
semi-bituminous	
sub-bituminous	
Wood:	
Ash	
Beech	
Birch	
Elm	
Fir	
Hardwood (several species)	7,000- 8,600
Locust	
Oak	
Pine	
Soft wood, resinous	

* These values depend, in many cases, on moisture content and/or purity of the sample measured; the heats of combustion are based on average samples and are presented here to indicate trends and relative values.

TABLE A.7 (Cont.)

Fuel	Heat of Combustion (approximate*) Btu/lb
Fuel Gases**	
Methane	23,800
Ethane	22,300
Propane	21,600
n-Butane	21,300
Acetylene	21,500
Hydrogen	61,000
Carbon Monoxide	4,300
Other Miscellaneous Fuels:	
Propane (liquid)	21,500
n-Butane (liquid)	21,100
Ethyl alcohol (liquid)	12,800
Carbon	14,100
Sucrose	7,100
Dynamite, 75%	2,300
Animal & Vegetable oils	15,000-18,000
Zinc (element)	2,300
Magnesium (element)	11,900
Phosphorus (element)	10,600
Sodium (element)	3,900
Charcoal and Coke	11,700-12,900
Straw (Buckwheat, Flax, Wheat)	5,600- 6,300

* See first page of Table.
** Btu values for gases are measured at constant pressure and are here rounded off to the nearest 100 Btu.

TABLE A.8

Classification of Some Urban Cellulosic-Base Fuels by Use or Function

Paper and Paper Products:	
Some window shades	Wrapping paper
Newspapers	Grocery bags
Magazines	Food containers
Books:	School paper
Hardback	Office paper
Paperback	Wallpaper
Cardboard boxes	Paper waste
	Litter, etc.

Wood	
Roofing shingles	Beds
Floors	Tables
Ceilings	Shelves
Walls	Cabinets
Windows	Fences
Doors	Piers and docks
Desks	Bridges
Chairs	Railroad ties

Cotton and Cotton Products:
Venetian-blind straps
Rugs
Draperies
Awnings
Tarpaulins
Bedding
Upholstery
Clothing

Similar classifications by use for other types of fuel could be constructed but are generally unavailable at this time.

From the above classifications of fuel types, we can see that there are many different kinds of fuels to be found in an urban area and that the method of description of fuel types depends, in most cases, on the usefulness of the method in explaining a particular aspect of urban fire vulnerability.

A.8.3 Distribution of Fuels in Urban Areas

The distribution of fuels in an urban area may be described by specifying the location of each type of fuel (described in A.8.) plus its proximity to other fuels in the immediate vicinity. Whether we are using a detailed mechanistic approach or a stochastic approach, fuel distribution is described by the typical average location of specified types of fuels and their typical proximity to other fuels in "homogeneous" urban subareas (such areas are discussed in A.2). By either approach, a fuel may be broadly classified as being in one of the following locations at any one time:

1. Interior (within enclosures).
2. Exterior (outside of enclosures in the open).
3. Part or all of the structural aspects of the enclosure.

Fuels may be generally fixed or transient, or both, and the method of describing fuel location by either approach will depend on how rapidly certain types of fuel can change location. We have taken transient fuels as those that can be observed to undergo rather large (horizontal or vertical) translations over the arbitrary period of several days. Perhaps this designation should be in terms of the history of a particular fuel.

Description of transient exterior fuel distribution for various urban land-use areas has been developed by Sauer et al.[1] In their report, Sauer et al. survey the distribution of ignition points in transient exterior fuels by use class (urban subarea) for Atlanta, Ga.; Boston, Mass.; Chicago, Ill.; Detroit, Mich.; New Orleans, La.; and Oakland, Calif.[1] The description of kindling fuels limits one to those kindling fuels that would be in direct view of the fireball; that is, they are of certain types like newspaper or rotted wood and are sufficiently large to burn long enough to spread fire to other combustibles in the vicinity. That report shows by survey that large cities exhibit many similarities in their ignition-point distributions and that these may be closely correlated with land-use areas. Bruce and Downs[2] have presented a method of surveying interior kindling fuels and have obtained data on primary ignitions for two selected cities (Boston and Detroit).

Fuel distribution in an urban area is exceedingly difficult to describe by any known technique. One basic difference between an urban fuel bed and that of the wildland is that urban fuels are distributed among nonfuels and hence any description of urban-fuel distribution must account for the arrangement of fuels relative to nonfuels (concrete, steel, vacant land, etc.). Fuels in urban areas are primarily located in either structures or vegetation, with structures usually having the greatest fireloads because of the typical preponderance of structures over vegetation in an urban area. Local urban fuel areas occur in discrete units separated by breaks in the fuel or by nonfuels. The most abundant urban fuel used in structures (including contents) is that of cellulosic base. Certain types of construction are recognized as containing greater amounts of fuel than other types (for example, wood frame vs noncombustible, respectively).

Most fuels occur between ground level and the second or third story (average height of fuel structures for all U.S. cities). The remaining fuels are located underground or in structures taller than the average height. On the other hand, some cities, even in the downtown area, will not have buildings much above the average height.

Sauer[1] in his study of transient exterior ignition points has postulated that there is a randomness of fuel concentration with respect to time and space, and that this randomness can be proved by repeated surveys using large sample sizes. The concept is a useful one that can be applied in future surveys.

The distribution of urban fuels can be obtained at various levels of description, depending primarily on the size of the area to be described. An estimation of fuel distribution usually is performed by spot surveys of "homogeneous" subareas for urban areas as large as cities. The distribution of fuels in local areas of fuel concentration can be described in detail by on-the-spot surveys.

A.8.4 Fields of View of Urban Fuels

The field of view of any urban fuel is what the fuel "sees" of its environment. The field of view of any fuel in its environment can be classified as follows: (1) the portion of the field of view of a fuel which "sees" the sky will determine the areas of the fuel which are exposed (most vulnerable to ignition) to the direct thermal radiation from a nuclear fireball, (2) that portion of the field of view, other than the above portion, which "sees" nondirect rays of light, and (3) that portion which does not see light. Knowledge of this parameter is necessary to determine the total amount of thermal radiation that could be received by fuels from the nuclear fireball. We are interested in describing the field of view of those fuels located neither so close to the ground zero as to be in the area of complete blast damage nor so distant from ground zero that the most flammable fuels will not be ignited.

Fields of view can be described for fuels in three general locations within the above annulus: interior (within enclosures), exterior (outside enclosures), and part of the enclosure itself. Interior fuels see less of the sky than exterior fuels do. The fields of view of the structural parts of an enclosure may be considered very limited since by our definition they "see" the exterior and interior finishes for the most part unless the structure is collapsed by the shock wave.

The most important portion of the field of view of fuels is that which "sees" the sky. This portion is called the "sky area factor" in Ref. 1 and means the amount of sky to which a fuel is exposed or the probability that a cm^2 of fuel will be directly exposed ("see" the sky) to the thermal radiation of a nuclear fireball.

The field of view of interior fuels may be described in terms of the following parameters:

Location of fuels within the enclosure.*

Area (dimensions), shape, number, location and orientation of openings (windows, doors, skylights, etc.) relative to its enclosure.

Height of the enclosure above the ground.

Location of the enclosure in the urban area.

Shape, area, and location of the profile of structures, vegetation, etc., as "seen" by the interior fuels.

Direction (N,S,E, or W) toward which the opening is facing.

The field of view of exterior fuels may be described in terms of the following parameters:

Location of exterior fuels in the urban area.

Height of the exterior fuels above the ground.

Shape, area, and location of the profile of structures, vegetation, etc., as "seen" by the exterior fuels in each direction (N,S,E or W).

Interior fuels depend on openings to "see" the sky. These openings usually have covers in the form of window glass, screens, blinds and other transparent or translucent materials that filter the light to various extents (windows open vs windows closed, etc.) because of the differences in thickness, composition, and geometry. Certain covers are opaque to all radiation. Openings may be shielded also by vegetation or structures which intervene between an interior fuel and the probable location of the fireball in the sky. Bruce and Downs[2] give the following transmission factors to account for the filtering effect of window covers:

---

* Salzberg[12] has described fuels in residential rooms to be randomly oriented 3 feet above the floor.

Covers	Transmission Factors
None	1.00
1 window screen	0.67
1 pane window glass	0.55
1 pane window glass + 1 window screen	0.370
2 panes window glass	0.306
2 panes window glass + 1 window screen	0.205

In an urban area the degree of shielding of one building by another can be considerable. This has been verified by Stanburg[35] by placing a powerful light in the position assumed for the explosion over a model of the city of Birmingham, England.

In order to "see" the sky, interior fuels must be located in enclosures that have openings to the exterior. Interior fuels may be classified according to whether their fields of view include:

a. Reflecting surfaces within the enclosure only (which see no openings to the exterior).

b. Openings directly exposed to the sky.

c. Openings not directly exposed to the sky but which see reflecting surfaces.

d. Openings not directly exposed to the sky which do not see reflecting surfaces.

In order for a surface to be nonreflecting, it must be completely absorbing. Common examples of reflecting surfaces that can be seen by fuels are the following:

a. Adjacent building walls that are painted white.

b. Surface of water area.

c. Surface of snow-covered ground.

d. Mirror hanging on wall in a room.

The fields of view of interior kindling fuels (potential ignition points) in 10 land-use subareas (see A.2.1) of Boston and Detroit were surveyed by Bruce and Downs using two portable instruments called "seen-sky" meters.[2] For this survey, it was assumed that (1) the subareas are

homogeneous (see A.2.1), (2) a 60-KT weapon is detonated in clear air at a 1732-ft altitude, (3) ground zero is located at the most probable target in the city, and (4) no obstructions exist between the fireball and a given potential ignition point. The fuels with respect to ground zero were in the "fire zone," which is defined as the annular region located beyond the 5-psi very severe blast-damage radius for frame buildings and out to the 3-cal/cm^2 thermal-radiation range for igniting dry newspaper. The meters were positioned at interior ignition points and sighted through structure openings. Observations were then made of the amount of the effective sky ring to which they were exposed. For a given ignition point, the effective sky ring is that part of the sky in which the nuclear weapon must explode in order to be seen by the point and effectively ignite it.

In an urban area, the items that most commonly obstruct the field of view of fuels are:

Structural aspects of buildings.

Vegetation, most commonly trees.

Utility poles, fences, vehicles of transportation, towers, and others.

Topography of the surface of the ground.

Exterior fuels generally will see more sky in the upward direction (skylights are an exception) than will interior fuels which are generally masked by ceilings, roofs, etc. for the typical case of a piece of fuel in a room. Masking features are vertical (edges of adjacent buildings), or horizontal (profile of the horizon: roofs, vegetation, etc., or overhangs over openings). Masking features decrease the probable effectiveness of openings in receiving direct thermal radiation from a nuclear burst. Anisotropic field-of-view patterns for some urban subareas can probably be shown, but no references were found in the literature.

A.8.5 Ambient Conditions of Urban Fuels at Time of Burst

A.8.5.1 Important Ambient-Condition Parameters

The ambient conditions of an urban fuel are the conditions of the fuel and its immediate surroundings at the time of nuclear weapon burst. Describing the ambient conditions of each fuel in an urban area would be and exceedingly complex task if it were not for the fact that such a description can be simplified by the use of certain generalizations. Many factors enter into the description of ambient conditions, but for our purposes of fire vulnerability, we can limit our discussion to the following more important parameters (not necessarily in order of importance):

Temperature of the fuel and of the air in the immediate vicinity of the fuel.

Moisture content of the fuel and of the air in the immediate vicinity of the fuel.

Speed and direction of the wind in the immediate vicinity of the fuel.

Age of the fuel.

"Treatment" of the fuel.

Most of these parameters are discussed in A.7 on Meteorology, and the information contained there is not repeated here. Our purpose here is to discuss ambient conditions and their determinability from Weather Bureau reports. Let us begin by dividing all urban fuels into exterior, interior, and part-of-the-enclosure locations, and then by discussing these separately with regard to the above parameters.

As can be shown, certain ambient conditions (such as atmospheric pressure) either exterior or interior can be more readily estimated from Weather Bureau information than others (such as local wind speed and air moisture content). These latter are largely influenced by whether the fuel is inside or outside the enclosure and by the local situation in the vicinity of the fuel. This implies that available Weather Bureau data cannot be used sometimes, at least in the form usually presented.

Most of the ambient-condition parameters are weather dependent and hence can generally be described according to the following breakdown of changes that occur in the weather:

Daytime-nighttime changes.

Seasonal changes (spring, summer, fall, winter).

Annual changes.

A.8.5.2 Temperature

The temperatures of exterior fuels, for example, undergo daily cycles as do relative humidity and wind. Exterior fuels, even if they are not exposed to the direct sunlight are warmed due to solar heating during the daytime and cooled by the absence of solar heating at nighttime. Solar-radiation data are reported by many weather-reporting stations throughout the U.S. at least every hour and by some stations continuously. Temperature variations occur locally where the effects of shielding by trees (or other vegetation) or structures from the direct radiation of the sun are

experienced. Weather-reporting stations generally report data on a statistical basis with time and geographical location. A reasonable generalization is that the temperatures of exterior urban fuels may be assumed to be in equilibrium at some reasonable height with the temperature of the air (most urban fuels are poor conductors of heat) reported by the nearest weather-reporting station. Exterior local variations in temperature between reporting stations can be assumed to be small compared to the differences in temperature due to variation in the geographic locations of cities. The temperatures of exterior fuels are also determined by the rate of evaporation of moisture (rain), which in turn has a synergistic effect with the speed and temperature of the wind (increase of wind speed or wind temperature will increase evaporation rate up to a point).

The temperature of interior fuels is regulated in most urban enclosures by thermostated heating and cooling devices. When these devices are turned off, the interior fuels and certain interior structural parts of enclosures may be treated as exterior fuels with regard to temperature providing either of the following happen separately, or they happen in appropriate combination:

1. The openings are large enough to permit the free flow of air between interior and exterior, or

2. Sufficient time elapses for the interior and exterior temperature to equilibrate due to heat transfer through nonregular openings or through the enclosure itself, which has certain insulating properties.

A.8.5.3 Moisture Content

The moisture content of exterior fuels may best be described by the intensity, duration, and prior history of precipitation on the fuels and/or by the relative humidity of the air during time of no rainfall. (The relative humidity of the air is a comparison of the amount of moisture in the air with the amount of moisture the air is capable of holding at the same temperature.) Hence, relative air humidity depends on moisture availability and air temperature. The term "effective humidity" is sometimes used; it is an index that takes into account the humidity of previous days. The equilibrium moisture content of interior or exterior fuels is an average that accounts for moisture absorption and moisture loss of the fuels. Moisture content can be related to the specific heat capacity of the fuels. Most U.S. urban fuels are generally drier in winter than in summer owing primarily to the fact that the relative humidity is lower in the wintertime.

The moisture content of interior fuels is generally regulated by the heating or cooling devices. Cooling devices in the warmer climate regions can be of either the refrigerated type, the evaporative type, or a heat pump. Evaporative types depend on the rate of water evaporation, and in this way contribute moisture to the interiors of evaporatively cooled enclosures. The refrigerated and heat-pump types do not contribute moisture unless they are equipped with humidifiers. Rogers and Miller[36] have indicated that the moisture content is practically independent of the kind of wood used in the interior of a house and that the moisture content of interior woodwork generally follows the outdoor temperature more closely than the air humidity. Extensive statistics are available from the building and lumber trades on moisture content of building materials with time and geographical location.

A.8.5.4 Wind Speed and Direction

The speed of the wind near interior fuels may be taken as zero if the enclosure is structurally sealed from the outside (no artificial ventilation). If opening covers (such as windows) are partially or entirely open, the speed of the wind in the enclosure becomes a description of the ventilation of the room by the exterior wind, which ventilation will influence the interior wind largely by the following parameters:

Speed of the exterior wind.

Angle the wind makes with the plane of the enclosure opening.

Temperature of the room (convective circulations).

Deflection of the wind by interior structural features.

Frictional forces of the wind.

A local exterior-wind analysis in a city has been described previously in Civil Defense Urban Analysis (1953)[4] which specifies the burning potential as a function of relative humidity and wind speed at 20 ft above ground, apparently based on the average height of buildings and based on the height above-ground that would reduce the effects of the major ground features. Exterior winds over a city may be expressed as an average velocity vector; however, the individual components of the wind are distributed according to the factors described previously.

We can, therefore, see that the widely varying seasonal patterns of weather across the country make averaging more important for nationwide surveys than for individual cities.

A.8.5.5 Age and Treatment of the Fuel

The age and treatment of urban fuels may be dealt with together, since the age of a fuel acts synergistically with the treatment of fuels. Woods, the most abundant urban fuel, undergoes many possible treatments other than those relating to the state of subdivision. Wood dust is pressed to form composition board, artificial logs for the fireplace, etc. The finishes wood can undergo are multifold, such as stains and paints. The finishes alter the surface properties of the fuel; the properties of which will vary with the age of the fuel. The age of wood in an urban area can often be estimated by the condition of these finishes. Some finishes are renewed from time to time, whereas others are not, either because of neglect or because the finish lasts the lifetime of the fuel. Certain wood finishes allow slow passage of moisture, whereas others actually absorb moisture from the air. The maximum age of U.S. urban fuels is much smaller than the maximum age of fuels in Japan or Germany, because of the longer history of these latter countries. Old wood is drier than fresh cut wood, and even the wood that is "aged" by lumber producers continues to lose moisture after it is put into a structure. All wood exterior finishes weather with age, but interior fuels are relatively unaffected by this process.

APPENDIX A

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APPENDIX B

NUCLEAR WEAPON BURST PARAMETERS

B.1 INTRODUCTION

Calculations of the effects of a nuclear explosion on a given target begin with specification of certain parameters of the weapon (total yield, partition of energy among thermal radiation, blast, ionizing radiation, etc.) and of the burst point (altitude above sea level, height above the terrain, latitude and longitude, etc.) The weapon effect of primary concern in this study, thermal radiation, is largely independent of such weapon characteristics as fission/fusion or yield/mass ratio. In most cases, the thermal pulse can be described adequately with knowledge of only two parameters, total yield and burst altitude. To determine the thermal flux at a given target on the ground, the geographical coordinates of the burst point and the target must also be specified; and if more than one weapon is involved, the time of detonation of each weapon as well.

From the above parameters, various characteristics of the explosion can be derived, such as the fractions of yield appearing as thermal radiation and blast energy and the time dependence of fireball size, temperature, and thermal emission. The effect of variations in yield and burst altitude on these characteristics is illustrated in B.2, while the effects of burst-point location and multiple-weapon attacks are discussed in B.3 and B.4.

Although only unclassified sources were used in the preparation of this section, they are believed to include the latest available information and to provide accurate models of weapon characteristics.

B.2 WEAPON-BURST PHENOMENA

B.2.1 Initial Explosion Phenomena

The initial phase of a nuclear explosion proceeds in a manner independent of the surrounding environment. Within a fraction of a microsecond after detonation, the fission products, bomb casing, and other debris have been raised to a temperature of several tens of millions of degrees Kelvin. Before the bomb vapors have had time to

expand appreciably (within a microsecond), a considerable fraction (~70%) of the total energy present appears as thermal radiation in the form of soft X-rays of several kev average energy, depending on the temperature of the weapon. The remainder is contained in the kinetic energy of the vapors, which expand (until they collide with the medium surrounding the weapon) at a velocity of several hundred miles per second.*

B.2.2 Low-Altitude Detonations (< 15 mi)

B.2.2.1 Air Bursts

In an air burst at sea level or low altitude, the primary thermal X-rays are absorbed within a few feet of the bomb, giving rise to extremely high temperatures within the initial fireball. The energy is immediately reradiated and again absorbed in surrounding cold air; hence, the fireball grows at high velocity as the radiant energy diffuses outward.

Since the radiation mean free path in air at these temperatures is large compared to the fireball dimensions, energy is rapidly distributed within the fireball, and the temperature throughout remains quite uniform as it grows and cools. The mass of hot gases in the region behind the radiation front is therefore referred to as the isothermal sphere.

The spectral distribution of radiation from the fireball can be approximated by the spectrum of a black body at the surface temperature of the fireball. Only a small amount of low-energy (visible and near-visible) radiation can escape from the immediate vicinity of the isothermal sphere at early times, however, since the shorter-wavelength photons are reabsorbed by the surrounding air.

A sudden rise in pressure is produced at the radiation front. As the fireball cools and the propagation velocity of the radiation front decreases, this pressure discontinuity develops into a strong shock wave, which separates from the isothermal sphere. This event ("hydrodynamic separation") occurs in low-altitude explosions when the temperature of the fireball has fallen to around 300,000°C (about 0.1 msec after detonation for a 20 KT explosion).**

After hydrodynamic separation,the apparent surface of the fireball is the location of the shock front, since the air heated to incandescense by its passage is opaque to the radiations of the isothermal sphere. The temperature of the shock-heated air is considerably less than that of the isothermal sphere, however, so that the apparent surface temperature and observed rate of energy emission of the fireball drop off

*Ref. 1, pp. 26, 68-69.
**Ref. 1, p. 71.

rapidly. The temperature of the isothermal sphere continues to fall, but remains higher than that of the surrounding shock front. The opacity of the shock front prevails until its temperature has fallen to around 1800°C. As the shocked air approaches this temperature, it emits and absorbs less radiation and gradually becomes transparent to the radiations of the isothermal sphere. The time at which the isothermal sphere can again be seen through the faintly incandescent shock front is known as "breakaway" (about 15 msec after a 20-KT detonation).

Following breakaway, the thermal emission and apparent surface temperature again increase as the unmasking of the isothermal sphere continues. A maximum is reached around 7000-8000°C (for small yields), when most of the radiation falls in the visible region and the fireball has nearly reached its maximum size. At later times the rate of emission falls off as the fireball continues to cool by radiation and expansion.

Thus, the rate of thermal emission and apparent surface temperature of the fireball in a low-altitude explosion are characterized by an extremely rapid rise to a maximum, followed by a rapid fall to a minimum and a slow rise to a second maximum. In a 20-KT explosion, for example, the thermal minimum occurs about 11 milliseconds after detonation (t_{min}) and the second thermal maximum at about 140 msec (t_{max}).* These times are roughly proportional to the square root of weapon yield, so that an approximate scaling law for t_{max} is:*

$$t_{max} \approx 0.032 \, W^{1/2} \text{ sec} \tag{B.1}$$

for W in kilotons.

According to Rogers and Miller,[2**] this expression predicts times about 30% too short for a kiloton yield and about 30% too long for yields of several megatons, with even greater errors at larger yields. An alternative formula to Eq. B.1 is therefore sometimes given,[3,4]

$$t_{max} \approx 0.044 \, W^{1/2} \text{ sec} \tag{B.2}$$

But, although Eq. B.2 would appear to be accurate for kiloton yields (according to ref. 2), it is even more in error than Eq. B.1 for megaton and larger yields. Evidently the scaling exponent should be somewhat smaller than 1/2.

*Ref. 1, p. 76.
**Ref. 2, p. A-22.

If Eq. B.2 is modified to fit the point for several megatons given in Rogers and Miller ($t_{max} \approx 1.5$ sec), it becomes

$$t_{max} \approx 0.044\ W^{0.43}\ \text{sec} \tag{B.3}$$

This equation is presumably more accurate at all yields than either Eq. B.1 or B.2.

In spite of its limited accuracy, however, Eq. B.1 has the advantage of convenience in that, if it is converted to megaton units, it becomes:

$$\begin{aligned} t_{max} &\approx 1.01\ W^{1/2}\ \text{sec} \\ &\approx W^{1/2} \end{aligned} \tag{B.4}$$

Within the range of 1-KT to several MT, this equation is good to ± 30%.

At altitudes above sea level, t_{max} is also roughly proportional to the square root of atmospheric density,[3,4] so that

$$t_{max} \approx (\ W\ \rho/\rho_o)^{1/2}\ \text{sec} \tag{B.5}$$

where ρ/ρ_o is the ratio of burst-point to sea-level atmospheric density. Since ρ/ρ_o is about 10^{-2} at 20 miles, the thermal pulse from an explosion at that altitude is about an order of magnitude shorter than that at sea level.

Atmospheric density up to about 80 miles is approximated well by the formula*

$$\rho/\rho_o \approx e^{-h/4.3} \tag{B.6}$$

where h is altitude above sea level in miles. This can be written:

$$\begin{aligned} \rho/\rho_o &\approx 10^{-h/9.9} \\ &\approx 10^{-h/10}, \end{aligned} \tag{B.7}$$

*Ref. 1, p. 531

which provides the convenient rule that atmospheric density changes by roughly a factor of 10 for every 10 miles change of altitude.

The fireball radius at t_{max} can be similarly scaled with yield. For near-sea-level air bursts, the radius is given approximately (within $\pm$ 30%) by:*

$$R_{max} \approx 180\ W^{0.4} \quad \text{ft} \tag{B.8}$$

for W in KT.

Taking into account both yield and density variations, Martin and Holton[5] give the following equations for t_{max} and R_{max} as functions of yield and burst altitude:

$$t_{max} = 0.82\ W^{0.42}\ e^{-0.09h} \ \text{sec} \tag{B.9}$$

$$R_{max} = 0.41\ W^{0.35}\ e^{0.0465h} \ \text{miles} \tag{B.10}$$

where W is in megatons and burst altitude h is in miles. These equations are probably quite accurate below 20 or 30 miles, but may be unreliable at greater altitudes. Substituting Eq. B.6 in the exponential terms involving h, it can be seen that Eqs. B.9 and B.10 assume that t_{max} varies as $(\rho/\rho_o)^{0.4}$ and R_{max} varies as $(\rho/\rho_o)^{0.2}$.

In the low-altitude range, the shape of the thermal pulse (normalized so that $t_{max} = 1$), the fireball temperatures at t_{min} and t_{max}, and the overall energy partition between blast and thermal radiation are largely independent of yield and burst height. Approximately 30% to 40% of the weapon yield is converted into thermal radiant energy, most of it in the visible and near-IR spectrum, and about 50% into blast energy. The first thermal pulse, emitted at high temperature, is very brief and represents less than 1% of the total thermal energy, whereas the second pulse contains 99% of the energy and is radiated over a much longer time at a lower temperature. The spectral distribution of the thermal energy is not quite that of a black body, being somewhat depleted in the ultraviolet and infrared.** However, it may be approximated fairly well by a Planck spectrum. For typical fireball temperatures this predicts about 10% of the energy in the UV, 40% in the visible, and 50% in the near IR. Of the total thermal energy, approximately 20%,

*Ref. 1, pp. 10, 77-78.
**Ref. 1, pp. 350-353.

50%, and 80% have been emitted by times t_{max}, 2 t_{max}, and 10 t_{max} respectively.*

An interesting second-order modification to the above statement concerning fireball temperatures applies to high-yield explosions: the fireball temperature at the second thermal maximum decreases slightly as yield increases. This variation is predicted by the Stefan-Boltzmann law for the power emitted by a black body,

$$P = \sigma A T^4 \qquad \text{(B.11)}$$

where T is the temperature of the body, A is the emitting area, and σ is the Stefan-Boltzmann constant. The power temperature of a fireball is thus defined by

$$T_P = \left(\frac{P}{\sigma A}\right)^{1/4} \qquad \text{(B.12)}$$

The total thermal energy emitted by the fireball is the time integral of its thermal power,

$$fW = \int_0^\infty P dt \qquad \text{(B.13)}$$

which can be written

$$fW = P_{max}\, t_{max} \int_0^\infty \frac{P}{P_{max}} \frac{dt}{t_{max}} \qquad \text{(B.14)}$$

$$= K\, P_{max}\, t_{max}$$

where P_{max} is power at t_{max} and f is the fraction of weapon yield emitted as thermal radiation. The integral has been evaluated for the weapon pulse given in Glasstone** and was found to be approximately 2.6 ± 0.5 (see Appendix D.3.2.7.1). Solving for P_{max}, we obtain

*Ref. 1, p. 357.
**Ref. 1, p. 359.

$$P_{max} \approx \frac{fW}{2.6\, t_{max}} \tag{B.15}$$

Substituting from Eqs. B.9, B.10, and B.15 into Eq. B.12 gives the fireball temperature at second thermal maximum:

$$\begin{aligned} T_{max} &= \left(\frac{fW/K\, t_{max}}{\sigma\, 4\pi\, R_{max}^2} \right)^{1/4} \\ &\approx \left[\frac{0.33\, W}{2.6(0.82\, W^{0.42}\, e^{-0.09h})\, \sigma\, 4\pi (0.41\, W^{0.35}\, e^{0.0465h})^2} \right]^{1/4} \\ &\approx 6800\, W^{-0.03} \ {}^{o}K \end{aligned} \tag{B.16}$$

where W is in megatons. For a yield of 20 KT, Eq. B.16 predicts a T_{max} of 7600 °K, which is in reasonable agreement with the value of 7700°C or ~8000°K given in Glasstone.*

B.2.2.2 Surface Bursts

When a nuclear explosion occurs on or near the surface of the earth, the explosion phenomena are affected in several ways. About half of the weapon debris and primary thermal X-rays are initially directed downward. Most of the weapon debris is reflected upward when it strikes the ground, while the thin layer of surface material which absorbs the primary thermal radiation is raised to very high temperatures and pressures and quickly blows off in an upward direction. A crater of considerable size (about 0.1 mi radius from a 1-MT surface burst on dry soil**) is produced by displacement and vaporization of surface material, and a strong shock wave is induced in the ground. The major fraction of the weapon energy is still contained in the thermal pulse and blast wave, however.

The reflected shock waves soon merge with the primary fireball shock wave. As this strengthened shock front travels out from the fireball, it remains opaque longer than the shock wave from an airburst of the same weapon; thus t_{min} and t_{max} are shifted to later times and the fireball radius at t_{max} is increased. In fact, the fireball from a surface burst of a weapon of yield W develops approximately as does that

*Ref. 1, p. 76.
**Ref. 1, p. 293.

of an airburst of yield 2W. Equations B.9 and B.10 thus become approximately[5]

$$t'_{max} \approx t\,(2W) = 1.1\ W^{0.42}\ e^{-0.09h}\ \text{sec} \tag{B.17}$$

$$R'_{max} \approx R\,(2W) = 0.5\ W^{0.35}\ e^{0.05h}\ \text{miles} \tag{B.18}$$

Because of the roughly hemispherical shape of the fireball, as well as the considerable amount of dirt and debris thrown up near the burst point, less thermal energy is received from a surface burst than from an air burst of the same weapon. Glasstone* estimates the effective thermal partition of a surface burst as one-half to three-fourths that of an air burst, with f tending toward the larger value as yield increases and distance decreases. Martin and Holton[5] take a partition halfway between these values, i.e. $f = 5/8 \times 0.33 = 0.21$. Note that this applies only to targets along the ground; from the air, where a larger area of the fireball can be seen, radiant exposures will be greater.

We may obtain the fireball power temperature at t_{max}[8] in a manner similar to that for an air burst. There is some evidence[8] that the shape of the thermal pulse, and thus the value of the integral in Eq. B.14, may be somewhat different for air and surface bursts. The variation seems to fall within the $\pm$ 20% measurement accuracy, however. Therefore the indicated value of K, 2.6, will be accepted as approximately correct for surface bursts.

Assuming the thermal partition to be 0.21, the radiating area (of the visible portion of the fireball) to be $2\pi\ R^2$, and substituting from Eqs. B.17 and B.18, we obtain

$$T'_{max} \approx \left(\frac{0.21\ W}{2.6(1.1\ W^{0.42}\ e^{-0.09h})\ \sigma\ 2\pi(0.5\ W^{0.35} e^{0.05h})^2} \right)^{1/4}$$

$$\approx 5900\ W^{-0.03}\ \ {}^{\circ}K \tag{B.19}$$

*Ref. 1, pp. 363, 366.

Thus the peak temperature of a surface burst is considerably less than that of an air burst of the same yield.

Above-surface explosions in which the fireball intersects the surface or is distorted by reflected blast energy will exhibit characteristics intermediate between those of air and surface bursts. The limiting altitude above which there will be negligible interaction between the fireball and ground can be assumed to be approximately equal to R_{max} for an air burst, given by Eq. B.10.

B.2.3 High-Altitude Detonations[4] (15 - 50 mi)

Below a critical altitude which depends on yield, the pulse shape previously described for low-altitude detonations is reasonably accurate. Above this altitude, the shock wave develops later and less strongly, and the thermal minimum is less pronounced as the shock front becomes transparent at higher temperatures. With increasing altitude, the fraction of yield appearing as blast is progressively reduced. A larger fraction of the thermal energy is emitted before breakaway (~12% for a multimegaton weapon at 30 mi), the energy emitted during the second maximum is correspondingly smaller, and the pulse is increasingly curtailed after t_{max}. Eventually, the thermal minimum and second maximum disappear completely, and the energy is radiated in a single rapid pulse of effective duration τ, where $\tau = t_{max}$, as given by Eq. B.9.

The critical altitude is about 20 miles for a 100-KT yield and 30 miles for a 100-MT. Thermal yield may be taken as 1/3 to 1/2 the total yield over the altitude range of 15 to 50 miles. The average fireball radiating temperature is probably not greatly different from that of a low-altitude burst; however, the UV and IR portions of the spectrum may be somewhat enhanced.*

B.2.4 Very High Altitude Detonations[1,4,6] (> 50 mi)

At very high altitudes the fireball, now large compared to the density gradient of the atmosphere, will tend to be distorted, becoming flattened below and elongated above. If the burst altitude is sufficiently great, the distortion will be extreme: only those X-rays emitted downward will be absorbed, producing a pancake-shaped region of excitation in the denser atmosphere below the burst, while those emitted upward will escape absorption completely. The thermal radiation at the ground from such a burst will then consist of two main components: (1) a brief flash of a few microseconds duration, the visible and near-visible tail of the high-temperature bomb vapor spectrum, followed by (2) a pulse of longer duration emitted by the excited region of the atmosphere.

* Ref. 1, p. 80.

A considerable difference in thermal yield is to be expected between the above types of burst, which may be described as upper-atmospheric and extra-atmospheric respectively. In the case of upper-atmospheric bursts, in which most of the primary X-radiation is still absorbed in the fireball region, the thermal efficiency f is roughly the same as that found at lower altitudes, i.e. about one-third. (Other characteristics are also similar to those of high-altitude bursts described in Section B.2.3.) In extra-atmospheric bursts, on the other hand, half or more of the primary X-rays are lost without significant atmospheric interaction, while the density of the excited layer is so low that re-emission of the absorbed energy may be too slow to be thermally effective. (Note that here is a case where a parameter of weapon design, yield/mass ratio, can have a considerable influence on "fireball" behavior, since the altitude and density of the excited layer, and therefore its rate of re-emission of energy, are dependent on the initial bomb temperature.) The other component of the thermal pulse, the thermal tail of the primary radiation spectrum, represents an extremely small fraction of the total weapon energy.

The transition altitude between upper-atmospheric and extra-atmospheric bursts has been variously estimated to be from around 50 mi (Miller and Passell,[6] for a bomb temperature of 10^7 °K or ~1 kev) to around 70 mi (Glasstone,[1] p. 323). In this regard it is worth noting that the Teak shot, an explosion in the megaton range at an altitude of ~50 mi, produced a definite though distorted fireball and a thermal efficiency characteristic of upper-atmospheric detonations (Glasstone,[1] pp. 50-52, 367).

B.3 BURST-POINT LOCATION

B.3.1 Effective Radiator Location

Because of the finite size of the fireball, the distance from its surface to a target will be somewhat less than the distance from the burst point to the target. This difference may be important when calculating atmospheric transmission for large-yield weapons. From geometrical considerations, it can be estimated[7] (when r > several fireball radii) that $r_{eff} \approx r - 0.6\,R_{max}$, where r_{eff} is the average distance from the target to the surface of the fireball, r is the distance to the center of the fireball, and R_{max} is given by Eq. B.10 or B.15.

Similarly, in calculating effective elevation angle of the radiator, the apparent center of the hemispherical fireball of a surface burst is located a distance of ~0.4 R_{max} above the ground.[7] The apparent center of an airburst fireball is, of course, coincident with the actual center.

Soon after detonation, the highly buoyant fireball is accelerated upward, reaching a maximum velocity of several hundred feet per second, so that its altitude increases somewhat during the thermal pulse. This

variation may require modification of the effective altitude for surface bursts; whether the effect will be significant for other burst heights depends on weapon yield and ambient density. The effective burst-point location for calculation of blast effects is identical with the actual burst point.

B.3.2 Range Attenuation of Thermal Flux

Attenuation of thermal radiation in the atmosphere is strongly dependent on meteorological conditions; the subject is discussed in detail in Appendix C. In vacuum, or at very high altitudes where scattering and absorption are negligible, the thermal flux falls off only as $1/r^2$. The energy intercepted by a normally oriented unit area is then*

$$Q = \frac{fW}{4\pi r^2} \tag{B.20}$$

Since one kiloton of yield is equal to 10^{12} calories, and assuming $f = 1/3$,

$$Q \approx \frac{W}{r^2} \tag{B.21}$$

where Q is in cal/cm^2, W is in kilotons, and r is in miles.

B.3.3 Range Attenuation of Blast Wave

The manner in which pressure, density, and velocity of the air immediately behind the shock front fall off as the front propagates out from the point of detonation is rather complex even for a free air burst. When the explosion occurs near the ground, a reflected shock wave is produced that may interact with the incident shock to complicate matters further. Since the primary interest of this study is in thermal effects, the subject of blast will not be considered here in depth.

Figure B.1 illustrates the interaction of incident and reflected blast waves from a near-surface burst. In part a of the figure, at a relatively early time after detonation, a portion of the shock front has reached the ground and has been reflected. The reflected shock travels through the air that has been heated and compressed by the incident shock, and its propagation velocity is therefore greater. Part b shows the situation at a later time, when a section of the reflected shock front has overtaken and fused with the incident shock. The fused shock front is referred to as the Mach front or stem. The distance from ground zero at which the Mach front begins to develop depends on weapon yield and height of burst.

Figure B.2, taken from Ref. 1,** illustrates the variation of peak overpressure on the ground as a function of distance from ground zero and burst height for a 1-KT explosion (assuming a homogeneous sea-level atmosphere at standard temperature and pressure, and near-ideal surface

* Ref. 1, p. 361.
** Fig. 3.67b, p. 139.

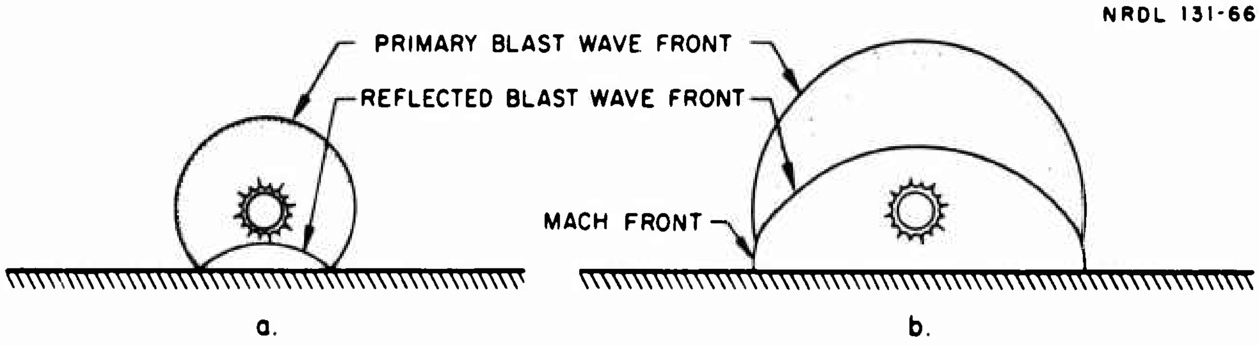

Fig. B.1 Incident and Reflected Blast Waves From a Near-Surface Burst

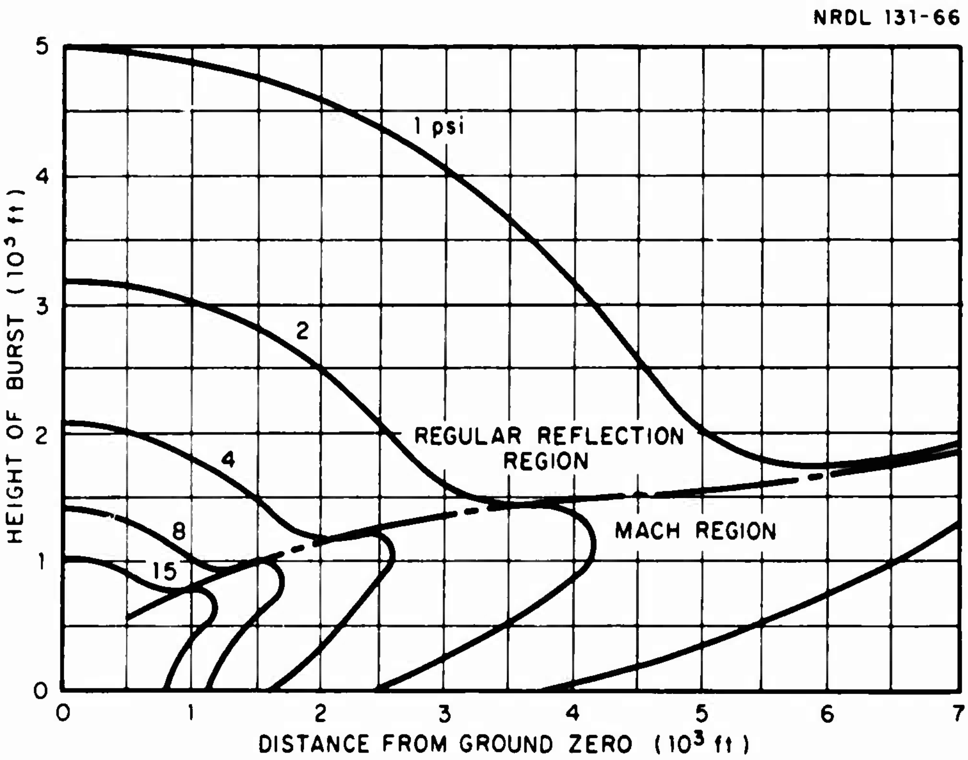

Fig. B.2 Peak Overpressure on the Ground Vs Height of Burst (W = 1 KT)

conditions). The broken line separates the Mach region from the region of regular reflection. Note that the distance from ground zero of any given overpressure contour passes through a pronounced maximum at a certain burst height. This is an optimum height of burst that maximizes the range from ground zero at which a particular overpressure is felt; conversely, for a given range, an optimum burst height exists that will maximize the overpressure received. Similar curves can be drawn for peak dynamic pressure, defined as $q = (1/2)\rho u^2$, where ρ and u are respectively air density and wind velocity immediately behind the shock front.

The ordinate and abscissa of Fig. B.2 scale as the cube root of the yield, that is,

$$\frac{H_2}{H_1} = \frac{D_2}{D_1} = \left(\frac{W_2}{W_1}\right)^{1/3} \tag{B.22}$$

The corresponding peak overpressure curves for a 1-MT explosion, for example, can be obtained by simply multiplying the scales of Fig. B.2 by 10. This scaling law has been found to apply well for explosions into the megaton range. However, it must be emphasized that the curves were derived from assumptions of a homogeneous standard sea-level atmosphere and near-ideal surface conditions. The first assumption is violated if the burst altitude and the target elevation differ by more than a few thousand feet, as they generally do in air bursts of large-yield weapons. Therefore, these curves should be considered only as indicative of the actual overpressures received from large-yield air bursts.

B.4 MULTIPLE-WEAPON ATTACKS

It is quite possible that in a nuclear-attack situation, several weapons may be detonated near certain U.S. urban targets, either simultaneously or consecutively. Reasons for the use of more than a single weapon include:

1. Payload limitations of delivery vehicles, requiring more than one weapon to accomplish destruction of large target areas.

2. Increased probability of at least one weapon on target, in the face of limited system reliability and accuracy and possible defensive countermeasures.

3. Possibly greater effectiveness of several small weapons compared to a single large weapon of equivalent total yield.

Only the last factor is discussed here, though certain of its conclusions

may apply to any multiweapon attack.

The simplest multiweapon situation involves two explosions. For example, a small weapon could be exploded in order to break glass and knock out window coverings over a large area, followed by a larger weapon that would ignite the internal fuels thus exposed; or one weapon might be exploded above the surface to optimize blast and thermal effects, and the other on the surface to maximize local fallout.

An example of simultaneous attack might involve warheads, each of yield W_T/n (where W_T is the total yield), delivered in salvo by a single missile. If the warheads are properly dispersed and detonated simultaneously (say within a time $t = t_{max}$), their thermal pulses and blast waves will reinforce at points on the ground between their respective ground zeroes. In effect, the total energy yield W_T is distributed more uniformly by several explosions than by one, and while destruction below the burst points is somewhat lessened, destruction some distance away is increased.

Even if the explosions are not simultaneous, the total destructive area may be increased under certain circumstances by use of multiple explosions. For example, if R(W) is the ground radius of a given overpressure contour for a given yield, then

$$R(W_T/n) = n^{-1/3} R(W_T) \qquad \text{(B.23)}$$

since blast radii scale as $W^{1/3}$. The area within the contour, however, is

$$A_n = n^{-2/3} \pi R^2(W_T) \qquad \text{B.24)}$$

and the total area for n weapons (assuming nonoverlapping contours) is

$$A_T = n A_n = n^{1/3} \pi R^2(W_T) \qquad \text{B.25)}$$

compared to πR^2 for the single large weapon. For $n = 4$ the total area of blast destruction is 60% larger than the area for an equivalent-yield single weapon.

A similar analysis may be performed for thermal damage. Experimental measurements by Martin[9] at NRDL of the variation with yield of radiant exposures required for ignition of various materials showed

that, for yields greater than ~ 100 KT, the ignition energy Q_i was proportional to about the one-fourth power of yield for a number of typical fabrics, household materials, and paper products. Solving Eq. B.21 for r,

$$r \approx \left(\frac{W}{Q}\right)^{1/2}$$

and substituting Q_i as a linear function of W (kW) we find that

$$r_i = k \left(\frac{W}{W^{1/4}}\right)^{\frac{1}{2}}$$

$$= k \quad W^{3/8} \qquad \text{(B.26)}$$

Thus the distance at which a given material can be ignited by a weapon pulse, disregarding atmospheric attenuation, is roughly proportional to the one-third power of yield. Addition of an exponential transmission term will cause ignition radii to scale even more slowly with yield.

In the absence of atmospheric attenuation, the total area within the ignition radii of n weapons of aggregate yield W_T is

$$A_T = n A_n$$

$$= n \pi R_n^2$$

$$= n \pi \left[n^{-3/8} R(W_T) \right]^2$$

$$= n^{1/4} \pi R^2(W_T) \qquad \text{(B.27)}$$

For n = 4 the total area of primary ignitions is 40% larger than the area for a single weapon of equal total yield. Moderate or severe atmospheric attenuation will increase the difference.

The above discussion assumes that weapon mass is linearly proportional to yield, so that total delivered mass is independent of the number of warhead- If smaller weapons are less efficient in terms of mass than large- the conclusions of the previous analysis may be partially inval far as the effectiveness of a given missile payload is concerned.

B.5 OTHER PARAMETERS

The other major effect of a nuclear explosion besides heat and blast is the production of various types of ionizing radiation, both immediately and through the formation of radioactive nuclei, which decay over a period of time. The magnitude of this effect is highly sensitive to such weapon parameters as fission/fusion ratio, weapon-case material, and weapon design. Initial and residual radiation are considered to be outside the scope of this report, since they are not expected to significantly affect the development of fires; however, residual radiation may have a considerable effect on control and cleanup after the attack. The effects of the electromagnetic pulse from the burst are also ignored, although they may affect communications during and following the attack.

One parameter not previously mentioned that may significantly affect thermal-radiation output in a very high altitude burst (> 50 mi) is that of proximity of the final missile stage to the warhead at the time of burst. Since this stage is the only nearby mass capable of absorbing the primary thermal X-rays, its presence may have a considerable influence on subsequent phenomena. The maximum effect might be expected if the warhead were submerged within the tankage and unexpended propellants of the stage, but whether this would increase or decrease the thermal output is unknown. Another possibility would be creation of an "umbrella" of tank fragments above the weapon, possibly using the unburned propellants for fragmentation. It seems likely that net X-ray emission downward could be increased by this configuration.

B.6 SUMMARY

The four weapon-burst parameters of primary importance in determining thermal and blast effects are:

1. Weapon burst-point location relative to target.
2. Total yield.
3. Burst altitude relative to sea level.
4. Number of weapons.

This approximate ranking is based on the rate of variation of thermal flux and blast pressures with change in a given parameter, the others being held constant: they vary as the second or greater power of

range, and about linearly with total yield, but relatively slowly with burst altitude and number of weapons. An exception to the statement regarding burst altitude applies to near-surface bursts, in which the characteristics of the explosion change rapidly with small changes in altitude.

APPENDIX B
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APPENDIX C

ATMOSPHERIC TRANSMISSION PARAMETERS

C.1 GENERAL

The thermal radiation emitted from the fireball of a nuclear burst must pass through the atmosphere before interacting with an urban area. This appendix identifies the parameters that influence the transmission of such thermal radiation and describes a method which may be used for expressing the effects of the atmosphere and its boundaries on the transmission of thermal radiation. The atmosphere is bounded at the bottom by the surface of the earth, upon which exist the structures, ground- and water-surface features, and vegetation of urban areas, and at the top by the transition between the atmosphere and outer space. In addition, a dense cloud layer could be either an upper or lower boundary, and a dense ground fog could be a lower boundary. Only the free-field distribution of thermal radiation upon a target is discussed here, since the shielding from thermal radiation, such as of one structure by another, by ground-surface topography, or by the attenuation of thermal radiation upon passage through target structures (window glass, screens, etc.), has been discussed in Appendix A.

Transmission parameters, which occur independently or as dependent groups, influence the amount, distribution, and duration of the thermal radiation delivered upon a target urban area and its surroundings. A literature search for these parameters has revealed almost one hundred references pertaining directly in content to atmospheric transmission; these were useful in preparing this appendix. The collation of parameters was achieved by consulting authorities in the thermal-transmission field and in part by the intuition of the authors. It was found that each of the parameters identified as influencing the transmission of thermal radiation from a nuclear weapon could be placed in one of the following broad categories:

1. The mechanisms of transport and loss.

2. The condition and variability of the atmosphere.

3. The condition and variability of the boundaries of the atmosphere.

4. The current methods of estimating thermal transmission from a nuclear weapon burst.

C.2 MECHANISMS OF LOSS AND TRANSPORT

C.2.1 Basic Geometry

The thermal radiation emitted by a nuclear detonation may be assumed to be evenly distributed in all directions away from the fireball. A target at some distance D from the fireball will receive a quantity of thermal energy that will vary inversely as the square of the distance D from the radiator, assuming the radiation traverses a vacuum and is completely unperturbed by the boundaries and contents of the atmosphere (clouds, target-surface albedos, etc.). Let us imagine that the total energy emitted falls upon the surface of a sphere whose radius is the distance D and whose total surface area is $4\pi D^2$. Under these conditions, we may calculate the energy received per unit area by an optimally oriented receiver using the following equation:*

$$Q \text{ (Radiant Energy)} = \frac{\text{Total Thermal Energy Emitted}}{4\pi D^2} \qquad (C.1)$$

The rate (irradiance) and duration of the thermal radiation delivered may be determined from the time-power curve of the thermal pulse and will vary with weapon yield, burst altitude, and other weapon-burst parameters, as indicated in Appendix B.

Thermal rays arriving at a target have traveled a direct or indirect path through the atmosphere. Burst altitude determines the maximum possible area on the surface of the earth that "sees" direct thermal radiation, according to the following equation:**

$$A_{max} = \frac{2\pi r^2 h_1}{r + h_1} \qquad (C.2)$$

where r = radius of the earth

h_1 = burst altitude above the earth's surface.

Passell[2] has expressed the corresponding theoretical limit of the ground range as a function of altitude:

*Ref. 1, p. 318.

**See next page for footnote.

$$EGR = r\cos^{-1} \frac{r}{r+h_1} \qquad (C.3)$$

where EGR = extreme ground range (distance along the earth's surface from ground zero)

r = radius of the earth

h_1 = burst altitude above the earth's surface.

---

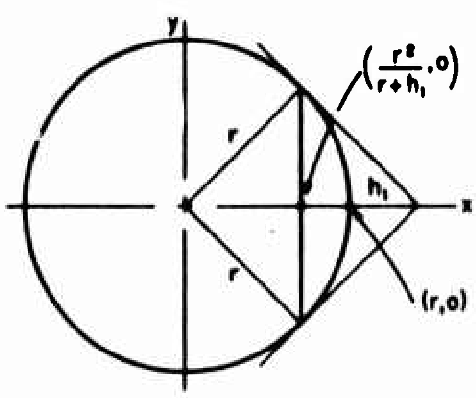
*Footnote for preceding page:

Derivation:

Let h_1 = burst altitude above surface of the earth

r = radius of earth

A_{max} = surface of revolution about the x-axis; the maximum theoretically possible area on the surface of the earth that "sees" direct thermal radiation.



Equation of circle is:

$$x^2 + y^2 = r^2 \qquad (1)$$

Differentiate (1):

$$\frac{dy}{dx} = \frac{-x}{y} = y' \qquad (2)$$

Equation for surface of revolution about x-axis between the required limits is:

$$A_{max} = 2\pi \int_{\frac{r^2}{r+h_1}}^{r} y\sqrt{1 + y'^2}\, dx \qquad (3)$$

*Footnote Cont.

Substituting (2) into (3):

$$1 + y'^2 = 1 + \left(\frac{-x}{y}\right)^2 = 1 + \frac{x^2}{y^2} = \frac{y^2 + x^2}{y^2} = \frac{r^2}{y^2}$$

$$A_{max} = 2\pi \int_{\frac{r^2}{r+h_1}}^{r} y\sqrt{\frac{r^2}{y^2}}\ dx \qquad (4)$$

$$= 2\pi \int_{\frac{r^2}{r+h_1}}^{r} r\ dx = 2\pi r\left(r - \frac{r^2}{r+h_1}\right) = \frac{2\pi r^2 h_1}{r+h_1}$$

The elevation angle, E, from some ground point may be determined by:[2]

$$\tan E = \frac{-\left(\frac{r}{r+h_1}\right) + \cos\Theta}{\sin\Theta} \qquad (C.4)$$

where
- E = elevation angle of the burst point seen from some ground point
- r = radius of the earth
- h_1 = altitude of the fireball
- Θ = angle subtended between the line joining fireball and earth's center and the line from earth's center to the ground point being considered.

Generally, the curvature of the earth is neglected except for very high altitude bursts, and hence the receiver is considered a flat plane.

Radiation is focused upon or diverted from a target. Any burst occurring in clear weather will direct a great deal of radiation upwards into space. A burst occurring above a layer of clouds will lose even more radiation into space due to reflection from the clouds. The radiation received by an optimally oriented receiver will be the combined result of such mechanisms as absorption, scattering, reflection, and radiative transfer into space; each acts to various extents and at various times, depending on specific prevailing conditions of the atmosphere, its boundaries (including any clouds), and the location of the burst relative to the boundaries (burst geometry). The most nearly horizontal paths of radiation from a given burst will be attenuated the most because these paths are through the greatest length of attenuating medium; although this may not be so for the case of scattered or broken clouds. It is convenient to divide the mechanisms of loss and transport into either absorptive or scattering processes and the phenomena that occur at boundaries. Let us now consider these mechanisms in greater detail.

C.2.2 Absorption

Absorption is responsible for a substantial reduction in the quantity of thermal radiation received by a target particularly for bursts above dense clouds and for other conditions of maximum absorption, which are discussed subsequently. Generally, absorption in a representative atmosphere is due to the atoms and molecules of gas and to the solid particles associated with dust, smoke, or smog. Thermal radiation may also be absorbed by liquid droplets, such as water droplets in clouds (including fog) or liquid chemical drops in smog.

Absorption occurs mainly in certain absorption bands separated by "windows" of negligible absorption. Gas molecules capable of absorbing radiation do so selectively. Atmospheric absorption is most effective at short wavelengths of radiation (ultraviolet). Water vapor (H_2O), ozone (O_3), oxygen (O_2), and carbon dioxide (CO_2) are the most important gaseous absorbers present in the atmosphere. Ozone alone, for example, absorbs the 0.20 to 0.29 μ wavelength region of any weapon fireball above 10 miles burst altitude to insignificance[3], for a receiver at surface level, and is the most important absorber for short wavelengths. Water vapor is the most important absorber for long wavelengths. Less important absorbers for long wavelengths are carbon dioxide, nitrous oxide (N_2O), methane (CH_4), and carbon monoxide (CO) gases.

Absorption is particularly noticeable as the distance from the fireball is increased. Because of absorption, the relative amount of ultraviolet radiation will be small at distances where thermal effects are important. If we could assume total attenuation due entirely to absorption (not really so), it would become possible to describe the thermal radiation received in terms of absorption only by

modifying Eq. C.1 with an exponential absorption coefficient K averaged over the whole spectrum of wavelengths.* Hence,

$$Q = \frac{\text{Total Energy Emitted}}{4\pi D^2} e^{-KD} \tag{C.5}$$

Water vapor is the most important gaseous attenuator in most atmospheres, and hence, the attenuation by absorption may be taken to a first approximation as a monotonic function of the absolute humidity.[3]

The absorption bands of water occur in the "red" end of the spectrum and contribute most to the attenuation by absorption in this region. Both water and carbon dioxide are strong absorbers in specific bands of the infrared wavelength region. Ozone absorbs strongly in the ultraviolet region, and this absorption may be expressed in terms of an atmospheric-ozone absorption coefficient given by Elterman,[4] who states that Vigroux ozone absorption coefficients and the latest (1964) data on ozone vs altitude concentration permit the calculation of atmospheric-ozone absorption coefficients up to 50 km for each of the desired wavelengths.

The absorption of solar thermal radiation by clouds has been investigated.[5,6,7,8] These representative reports are cited in this appendix because of the similarity of the sun with nuclear-weapon fireballs which is considered in C.5.

C.2.3 Scattering

All wavelengths of thermal radiation are scattered, or in other words, are diverted from the most direct path between the fireball and the ground to some degree. Nitrogen and oxygen are the most important gaseous scatterers; however, scattering caused by them is not so important as scattering caused by particles of dust and smoke and the water droplets normally present in the atmosphere.

The scattering due to molecules in the air may be expressed by applying a scattering coefficient (Rayleigh):[9]

$$\sigma = \frac{32\pi^3 \alpha^2 N}{3\lambda^4} \tag{C.6}$$

where σ = scattering coefficient (cm^{-1})

$\alpha = 1.08 \times 10^{-23}$ (constant between 0.3 and 0.7 μ) (cm^3)

*Ref. 1, p. 361.

N = molecular density (cm^{-3})

λ = wavelength of light (cm)

From Eq. C.6 we see that the Rayleigh scattering coefficient is inversely proportional to the fourth power of the wavelength.

Scattering reduces the amount of direct radiation received by a target by changing the direction of radiation. Radiation received at a target is commonly described as having direct and diffuse components. Ultraviolet, visible, and infrared wavelength radiation, are attenuated to different extents.

Scattering due to particles in the air is strongly dependent on the concentration and size of the particles as well as on the specific wavelength of radiation. If only a satisfactory estimate of the attenuation due to scattering is desired, it is practical to use a scattering attenuation value averaged over all the wavelengths. Since scattering always occurs in addition to absorption, the K (average absorption coefficient) of Eq. C.5 cannot really be considered a constant. Hence, a more useful expression in terms of the fraction of direct and scattered radiation that is transmitted is as follows:*

$$Q = \frac{\text{Total Energy Emitted}}{4\pi D^2} \times \bar{T} \tag{C.7}$$

where $\bar{T}$ = average transmissivity

Many parameters influence the assignment of values for transmissivity in Eq. C.7 for the variety of possible conditions. It will be our purpose to present values of transmissivity (or multiplying factors by which T may be calculated) for typical situations.

An equation for evaluating values of $\bar{T}$ for near-ground-level paths has been given by Gibbons[3] in the form (plotted in Fig. 3 and Fig. C.1):

$$\bar{T} = e^{-K_1 \frac{S_T}{V}} \left(1 + K_2 \frac{S_T}{V} \right) \tag{C.8}$$

where $\bar{T}$ = average transmissivity

S_T = effective slant range for thermal radiation

*Ref. 1, p. 361

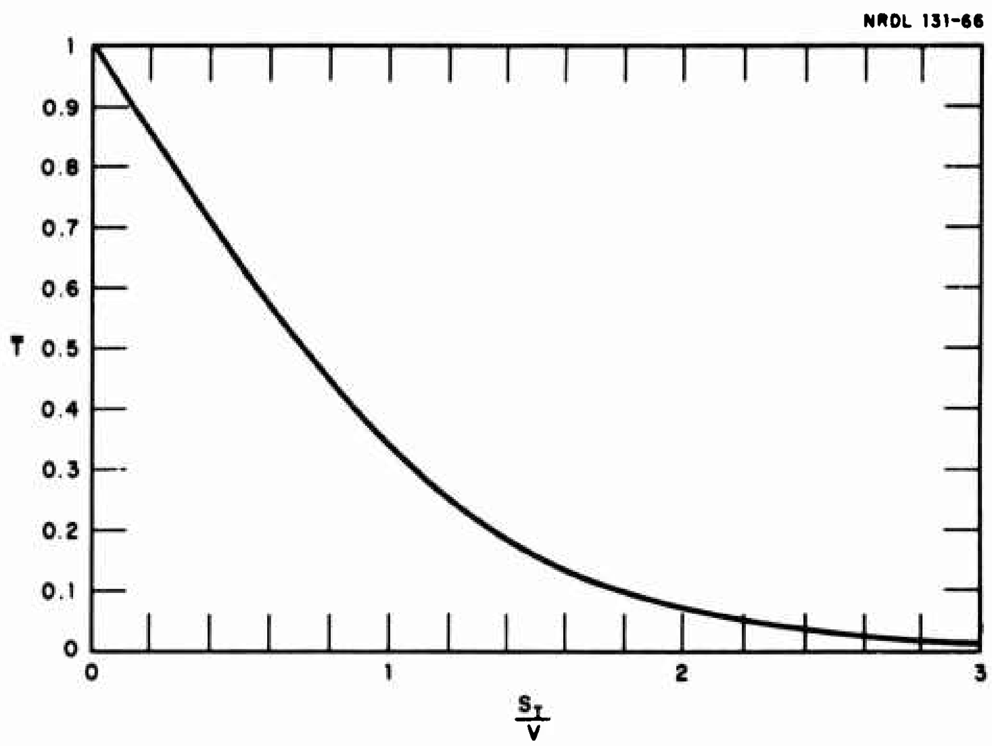


Fig. C.1 Transmissivity ($\overline{T}$) Vs the Ratio Slant Range (S_T) Over Visibility (V)

K_1 and K_2 = coefficients that depend, in general, upon wavelength (experimental)

V = visibility as commonly observed. (See Section C.3.1)

Equation C.8 is obtained from the more general equation:

$$\bar{T} = e^{-\sigma D} (1 + 0.7\ \sigma D) \text{ by assuming } \sigma V \cong 2.$$

σD = optical thickness as defined in footnote p. 214.

Glasstone* has stated that the instantaneous value of T at the instant Q is measured cannot be determined with a precision of better than about ± 20%.

Gibbons[3] has indicated that the attenuation of energy due to scattering is roughly proportional to the attenuation of energy due to water-vapor absorption for visible and near-infrared wavelengths and that the attenuation coefficient for scattering is a monotonic increasing function of relative humidity. Attenuation by scattering is known to remove energy primarily from the "blue" end of the energy spectrum. Equation C.8 is discussed further in C.3.1 and C.5.2.

The mechanism of scattering is complex to describe, and several types of pathways are known to contribute to the process. For example, radiation that is initially scattered may be reflected away from a target and "lost," or radiation may be "scattered-in" by a series of favorable deflections to impinge on the target concerned. According to Gibbons[3], the overall thermal transmissivity for a fireball of less than 0.25-mile (1320 ft) altitude burst (below which the atmosphere may be considered roughly homogeneous, since the aerosol number density, or number of suspended particles per unit volume, at 0.25 mile is about three-fourths that at sea level[10]) was found to be approximately equal to the transmissivity for scattering only (including scattering-in) for 0.55 μ radiation. Also, the attenuation coefficient for scattering decreases with increasing wavelength. For this reason, the transmissivity of energy on the basis of scattering-out only (not including scattering-in) for wavelengths greater than 0.55 μ may also fit the overall transmissivity. This fit has been shown to be the case by Gibbons[3] who has chosen 0.65 μ (a rather strong attenuation by scattering) as the wavelength that may be considered representative of the thermal radiation given off by a megaton burst in the atmosphere. It is considered representative in the sense that the scattering-only transmissivity for it will approximately equal the actual transmissivity for the entire thermal pulse.

*Ref. 1, p. 362.

Multiple scattering is responsible for visibility becoming less reliable as a factor in determining the amount of energy received at a given distance under certain conditions, such as a clear atmosphere with no fog, rain, or industrial haze, as discussed later in C.3.1.

The size of water droplets is an important scattering parameter in that droplets up to about 5 μ diameter show selective scattering of visible radiation, and if larger (fog), are nonselective scatterers of visible radiation and therefore colorless.

Mechanisms of scattering through the atmosphere have been investigated for different purposes. References 12 to 20 inclusively are a representative selection in addition to those already cited.

C.2.4 Boundary Phenomena

The possible boundaries of the atmosphere of interest have been previously described in C.1. Losses in thermal energy that occur across boundaries and the processes or mechanisms at boundaries will be discussed separately, but the boundaries we will consider will be constrained by the burst-target geometry (configuration). On a clear day, the bounds of the atmosphere are the surface of the earth and the top of the atmosphere, and a burst at any height will involve only these boundaries. However, a cloud layer may become a lower or upper boundary for the purpose of estimating the transmission of radiation. Ground fog may be a lower boundary. In addition to horizontal layers of clouds and fog, the boundaries that thermal radiation "sees" because of the vertical distribution of clouds (and fog) will possibly be significant. The effects of cloud layers on thermal radiation and the reflection of thermal radiation from a variety of surfaces of the earth are described in further detail in C.3.3 and C.4.1.

C.3 ATMOSPHERIC CONDITIONS

C.3.1 Visibility and Meteorological Range

Since visibility has not been treated previously, the distinction between visibility and meteorological range should be pointed out. Visibility is an estimate of the visual range for a locality at which an object of reasonable size can be distinguished from its background in daylight.[21] Generally, visibility is estimated by noting the distance at which the farthest of a series of objects at known distances can be seen fairly clearly by an observer in daylight. By replacing the objects with lights, visibility measurements can be made at nighttime. Meteorological range (which is defined in terms of a 2% liminal, or threshold contrast) is a more clearly defined concept than visibility. Gibbons[3] concludes on the basis of his own experimental results that the commonly observed visibility, such as that observed at airport weather

stations, is about one-half the meteorological range, and has pointed out that Duntley[22], in a special experiment to distinguish the two, has reported visibility to be about three-fourths of the meteorological range. Visibility as ordinarily reported depends on a number of variables such as:[3]

a. Absorbing and scattering properties of the atmosphere.

b. Angular subtense of the object (from the location of the observer).

c. Color of the object.

d. Background luminance.

e. Observer's interpretation of liminal contrast.

Gibbons[3] states that daylight visibilities do not depend appreciably on the absorbing properties of the atmosphere or on the position of the sun and that because of the ill-defined nature of visibility as used in Eq. C.8, this equation should be treated as purely empirical.

C.3.2 Composition of the Atmosphere

A "clear standard atmosphere" is one that may be called "clear," although it does contain a haze component (meteorological range = 15.5 mi (25 km) at sea level) and has been defined by Elterman[10] for attenuation in the visible and infrared windows. Elterman's model is based on a Rayleigh atmosphere with an aerosol component based on recent sea-level and high-altitude measurements. As indicated by Passell,[2] the condition of perfect clarity is rare, and hence it is proper to use "visually judged clear" data. The Handbook of Geophysics,[23] and handbooks of meteorology are standard references for the variation in the composition of the atmosphere with altitude. A complete description of the standard atmosphere on which Elterman's model is based can be obtained from the U.S. Standard Atmosphere, (1962, U.S. Government Printing Office, Washington 25, D.C.). Nawrocki[24] has compiled a handbook of upper-atmospheric processes of which Chapter 10 is devoted to the transmission of electromagnetic waves through the atmosphere.

The variation of density with altitude is discussed briefly in Appendix B, in conjunction with the calculation of weapon-burst parameters. Elterman's model[10] indicates that 90% of the gaseous material and 99% of the atmospheric water content in a "clear standard" atmosphere are below 10 miles' altitude, as well as about 90% of the relatively less important infrared-absorbing gases mentioned previously.[3] Elterman's model also indicates that 99% of the particulate material of

the atmosphere is below 10 miles altitude. Hence Gibbons[3] has concluded that practically all the attenuation of thermal energy between the fireball and any ground point will occur in the lower 10 miles of the atmosphere. This attenuation does not include ozone absorption (0.20 to 0.29 μ), since somewhat less than one-half of the amount of ozone above sea level will be below 10 miles.[3,25] However, the amount of radiant energy in this wavelength range reaching the ground from a burst above 10 miles would be practically zero.[3]

C.3.3 Aerosols

Atmospheres over urban areas containing large quantities of aerosol particles are considered polluted atmospheres, and much data on pollutants has been gathered by the Public Health Service from a small number of measuring stations across the nation. Undoubtedly, there are atmospheres that naturally contain rather large amounts of aerosol particles, but these occur rather rarely and under special meteorological conditions. Motor-vehicle exhausts are the prime contributors to air pollution in urban areas (main contaminants: hydrocarbons and nitrogen oxides). Other important contributors are large power plants and the open burning of wastes. The solid and liquid particles (haze), which often are the products of a series of complex reactions, are called aerosol particles and are caused primarily as the result of human activity. On perhaps an average of one-third of the time, these particles concentrate at altitudes of 500 feet or less (varies with lapse rate) and form large slowly drifting "seas" of pollution above major cities or "chains of cities."[26] The Public Health Service has recently activated computer monitoring stations that provide 24-hour-a-day measurements of CO, SO_2, NO, NO_2, O_3, total oxidants, and total hydrocarbons at one location in each of 9 cities, and also 200 noncomputerized stations in urban and rural areas. The usefulness of these data has not been reported for our purposes; however, they should be investigated.

White smoke attenuates thermal radiation in much the same manner as fog. Dense smoke can reduce the thermal radiation received to a tenth of the amount received without the smoke.* Smog is a mixture of solid, liquid, and gaseous components; its solid particles are of major importance in attenuating radiation by scattering. In typical smogs, the particles appear to be in the same size range as the particles in natural haze.[14] Smog particles are very diverse in nature and it is probable that they have indices of refraction that are of about the same magnitude as those of ordinary haze; hence, absorption and scattering may be treated independently in smogs not containing too much smoke.[14]

*Ref. 1, p. 321.

Haze and fog are commonly reported by meteorologists in terms of visibility, but the size distribution and concentrations of particulate matter with altitude are not reported.

Duntley[27] has defined an "optical standard atmosphere" in which the size distribution of the scattering particles are the same at all altitudes, but in which the relative number of particles per unit volume decreases regularly with altitude.

Elterman[4] establishes aerosol attenuation coefficients from available transmission measurements in conjunction with suitable vertical aerosol-density distribution. The aerosol particle-size distribution is considered unchanged with altitude. Thus,

$$B_p(h) = B_p(0) \cdot \frac{N_p(h)}{N_p(0)} \tag{C.9}$$

where h = altitude in km

$B_p(h)$ = aerosol attenuation coefficient as a function of altitude (km^{-1}).

$B_p(0)$ = aerosol attenuation coefficient in km^{-1} at sea level for meteorological range = 25 km (15.5 mi).

$N_p(h)$ = aerosol number density as a function of altitude (cm^{-3}).

$N_p(0)$ = aerosol number density in cm^{-3} at sea level for meteorological range of 15.5 mi (25 km).

State-of-the-art data for determining the three parameters cited in Eq. C.9 are reviewed by Elterman.[4]

C.3.4 Clouds

A layer of thick clouds below an air burst will reflect or scatter much thermal radiation out into space, and the radiation that does pass through the cloud will be highly scattered, which therefore further decreases the amount of radiation received. Only a small amount of radiation is directly received through such a cloud layer. If the burst occurs beneath such a layer, a great deal of thermal radiation is reflected or scattered downward and more will be received by the target. Whether a burst is above or below clouds makes a significant difference in that clouds can dramatically alter the amounts of thermal radiation received. The number of parameters involved is complex, and

the data on the parameters believed to be necessary are largely unavailable, at least in the form to fit any existing scheme at the time of burst.

Cloud phenomena have been the object of quite a large amount of research interest for over 30 years; but, the amount of consistent data on clouds is generally too sparse for statistical treatment. Table C.1 presents a combined cloud-fog classification scheme. Clouds are primarily classified according to their altitude, thickness, and form. Fog, which is considered to be a cloud on the ground, is generally classified by its primary process of formation.

A brief review of previous investigations of transmission through clouds follows. Passell[2] states that such transmission could be calculated if the thickness, liquid content, droplet size, size and distribution of solid haze particles, and the reflectivity of the earth's surface were known. He indicates that the transmission of solar energy is 80% for vertical rays and 15% for rays 5° above the horizontal on an average "clear" day at sea level, and that taking this as a 100% baseline, the transmission varies for light cloud (30%) to dense cloud (3%). The use of such solar data is limited to the daytime.

It appears there is quite a large amount of information and data on transmission of thermal radiation where the source is located above the clouds, but data for sources under, within, or between clouds are generally unavailable.[5,8,11,17,31-35] However, approximations for such cases have been made.[3,11,35] The case of transmission through a cloud or atmosphere during precipitation (rain, snow, hail, etc.) has not been investigated.

Atlas[36] points out that, whereas meterologists report the percent sky obscured, cloud type, cloud-base altitude and occasionally cloud-top altitude, the attenuation models require a mathematically defined volume occupied by cloud and the spatial distribution of particle size and concentration. He also points out that, in cloudy skies, significant changes occur in minutes, whereas for noncloudy skies, such changes in specific attenuators occur in hours.

Haurwitz[32,33] has related cloud types with the percent of insolation (total solar radiation) cutoff as follows:

Cloud Type*	Insolation Cutoff
High clouds	20%
Middle clouds	20% to 60%
Low clouds and fog	65% to 80+%

*Refer to Table C.1.

TABLE C.1

Classification of Clouds[28]

Classification	Form*
I. High Clouds (mean lower level $\simeq$ 20,000 feet)	
A. Cirrus	b
B. Cirrocumulus	b
C. Cirrostratus	c
II. Middle Clouds (mean upper level $\simeq$ 20,000 feet, mean lower level $\simeq$ 6,000 feet)	
A. Altocumulus	a or b
B. Altostratus	c
III. Low Clouds (mean upper level $\simeq$ 6,000 feet, mean lower level close to ground)	
A. Stratocumulus	a or b
B. Stratus	c
C. Nimbostratus	c
IV. Clouds With Vertical Development (mean upper level $\simeq$ 20,000 feet; mean lower level $\simeq$ 1,500 feet)	
A. Cumulus	a
B. Cumulonimbus	a
V. Fog (Clouds on the Ground)[29,30]	
A. Air-Mass Fogs	
1. Advection fogs (cooling caused by transport of warm air over a cold surface)	
a. Land-and-sea-breeze fog (occurs in summer, New England coast)	

TABLE C.1 (Cont.)

b. Sea fog (occurs in summer, California coast)

c. Tropical air fog (occurs in southeast U.S. and east coast)

d. Steam fog (occurs only over water)

2. Radiation fogs (cooling caused by radiation)

a. Ground fog (occurs in Appalachian valleys and California valleys [tule fog]

b. High inversion fog (occurs in winter in low valleys of far west)

3. Advection-Radiation Fogs (nighttime radiational cooling of air that has moved inland from the sea during the day)

4. Upslope Fogs (cooling of air at its dewpoint by adiabatic expansion as the air moves to higher elevation; occurs in the Great Plains)

B. <u>Frontal Fogs</u>

1. Prefrontal fogs (warm front; occurs in Middle and North Atlantic coast states in winter and in Appalachian valleys)

2. Postfrontal fogs (cold front; occurs in Midwest U.S. during polar air-mass outbreaks)

3. Front passage fogs (occurs in entire U.S.)

---

*Form a: Isolated heap clouds with vertical development during their formation, and a spreading out when they are dissolving.

Form b: Sheet clouds that are divided into filaments, scales, or rounded masses, and that are often stable in the process of disintegration.

Form c: More or less continuous sheet clouds, often in the process of formation or growth.

Aldrich[30] has determined that, on the average for California stratus clouds, 78% of the incident solar radiation is reflected from the top of the cloud layer, 20% of the incident solar radiation is transmitted, and 2% is absorbed. The last value indicates that the absorption of solar radiation by fog and clouds under "ordinary conditions" is not great.[5]

Bricard [37] has measured the average radii of the droplets in various types of clouds as follows:

Cloud Type Measured	Average Droplet Radius (cm)
Nimbostratus	1×10^{-3}
Stratocumulus	8×10^{-4}
Cumulus	5×10^{-4}
Stratus	4×10^{-4}

Hewson[5] has theoretically calculated the absorption of solar radiation for various cloud thicknesses and types and has pointed out the variation of droplet size within a given cloud (droplets are larger, in general, at the cloud base).

Passell[2] reports that measurements of the atmospheric turbidity have been made with clouds no closer than several tens of degrees from the vertical to the sun at each of some 30 U.S. Weather Stations since August 1961, and that if the source-elevation angle E is known (Eq. C.4), the transmission factors through clouds to a surface normal to the direct rays can be derived by multipying the horizontal surface transmission factors by a correction factor, as applied by Passell to the data of Haurwitz,[32] which is:

$$\left[\left(\frac{\pi}{2}\right) + E\right]\left(\sin E\right) / \pi$$

Jiusto[34] has modeled the chief types of fog (radiation: inland, and advection: coastal) by assigning representative numbers to the following parameters:

a. Drop diameter.
b. Drop size range.
c. Droplet concentration.
d. Liquid water content.

e. Vertical depth of fog (1. typical, 2. severe).
f. Horizontal visibility.
g. Nuclei size.

Korb[8] has shown in a number of cases that absorbed solar energy provides enough energy to evaporate cloud droplets. Eldridge[38] has measured diffuse transmission through clouds over slant ranges from 0.5 to 9.0 km using an intense light source attached to a balloon and presents results for dense fog (Visibility = 1 to 2.5 km), for clear atmosphere below clouds, for light fog (Visibility = 3 to 8 km), and for haze or light fog-drizzle below clouds.

These reports, cited on transmission through clouds, contain many cross references for someone pursuing the subject and are presented here as illustrative of some of the more applicable reports that were available to the authors. They do indicate in a gross fashion the efforts that have been made in this area.

C.3.5 Variations in the Atmosphere With Time and Location

It would be impossible in the present report to indicate all of the variations in the various components of the atmosphere with time and location. Many such changes are regularly reported by the Weather Bureau and others are not. A simple reference book in elementary meteorology, such as Taylor's[28], presents major weather patterns, and other standard meteorological texts contain the variations of gases, liquids, and solids in the atmosphere with time and location. Such data are dependent on the availability of frequent, if not continuous, measurement together with methods of expressing the results. Certain fundamental processes occurring in the atmosphere and at its boundaries are recognized as the basis for weather and the observed variations. Several of the most fundamental of these are the wind and the thermal cycles of evaporation, warm air rising, precipitation, and the decrease in temperature with altitude. We are thus limited here to presenting several of the more dramatic or significant variations found during this study.

One method for describing the variations sought is to divide the country or regions into areas (locations) within which the probabilities of occurrence of a particular variation are approximately equal for some specified time period. For example, there could be the variation of visibility, the frequency of a particular type of cloud over a certain region, or the wind speed and direction with the time of day. It can be seen that there exist variabilities in the amount of thermal radiation transmitted because of variation in the above parameters.

Recently, the Tiros weather satellites have made possible the measurement of nationwide cloud or snow cover. More use of these in

estimating thermal-radiation transmission is anticipated. Atlas[36] has analyzed yearly weather patterns and has made estimates, such as the following, as derived from monthly and seasonal distribution of mean daily transmissivity of clear-day solar radiation:

1. With no clouds in the sky most of the U.S. receives 65% or more of the available radiation.

2. In the Southwest, $\overline{T}$ is greater than 75%.

3. With a 3/10 cloud cover, $\overline{T}$ for Southwestern U.S. is 35%, and for the Northwest U.S., with 3/10 cloud cover the $\overline{T}$ average is 15%.

4. Averaging over all weather conditions and all days, the extremes of $\overline{T}$ were selected:

Great Lakes (winter and fall): 35%.
Arizona-New Mexico (spring): 70%.

5. The mean average daily transmission value varies between 0.25 and 0.80 as scattered clouds (1/10 to 5/10) and broken clouds (6/10 to 9/10) pass over respectively with an overall $\overline{T}$ value of about the same as that for uniform thin clouds (0.55).

6. Specific locations may have $\overline{T}$ values varying significantly from the above averages. For example, in 1955, the Los Angeles Airport had $\overline{T}$ values 6% higher than the City of Los Angeles because of smog, and the values may be higher now.[23] The average $\overline{T}$ values of selected cities are reported by the U.S. Weather Bureau, and the variations among these measurements can be compared.

7. The mean transmissivity for the U.S. is 57%.

Jiusto[34] has surveyed the occurrence of supercooled fogs in the U.S. and concluded that the Pacific Northwest has the greatest frequency of occurrence (46 to 213 hours of supercooled fog in the average winter season). The occurrence of some other types of fogs has been indicated in Table C.1.

Tilson[26] has indicated that there is evidence of an increase of the total CO_2 content of the air by 15% since the 19th century, and that the CO_2 may be 50% higher by the year 2000 (long-term variation) than in preindustrial days, owing to fuel combustion and metabolic processes. The latter indicated value is based on fairly speculative estimates, but if accurate could reduce the infrared thermal energy transmitted through real atmospheres at the present time and influence the atmosphere by, for example, increasing the temperature of the earth by a few degrees.

C.3.6 Variations in the Atmosphere With Thermal Radiation, Nuclear Radiation, and Blast

The effects of blast, thermal radiation, and nuclear radiation on the atmosphere are not well documented; thus, only the most preliminary estimates of the magnitudes of these effects can be made here. Since thermal radiation generally precedes the blast wave and most prompt nuclear radiation is relatively "short-pathed," the dynamic sequence of these phenomena becomes important. Let us consider the thermal and nuclear radiations first. The effect that the arrival of the blast wave will have will depend on the state of the atmosphere during and after the time of the thermal pulse.

Thermal radiation vaporizes water droplets and may cause clouds to dissipate because of the large amount of heat (Korb[8] has shown that, in a number of cases, sunlight provides enough energy to vaporize cloud droplets). The subsequent cooling of the atmosphere causes clouds to reform, or perhaps to fall as rain. This reforming has been recorded on films of actual weapon tests where clouds were seen between the fireball and the camera.

Nuclear radiation interacts with the air to form rather large quantities of ozone, nitrogen oxides, etc., that have some effect on thermal radiation before t_{min}. However, since these substances are unstable and in low concentration, they will have only a small effect in attenuating the total thermal radiation emitted after t_{min}. The possible ionization or nucleation effects of nuclear radiation do not occur fast enough to cause attenuation. The thermal volatilization of surface materials and the formation of new attenuators by chemical reactions undoubtedly also occur.

Blast overpressures can probably disperse clouds, but the mechanism by which this occurs has not been investigated. The shock wave probably does not materially displace clouds for large distances due to its method of propagation, except close in to the expanding fireball. The disappearance of clouds might be caused by blast in which case the phenomena is probably due to the rise in temperature resulting from adiabatic compression as the wave passes. The magnitude of this effect and its influence on transmission are unknown. Surface-burst blast effects on transmission are more pronounced, especially at early times, because particles are thrown into the attenuating medium before all the thermal energy has been emitted. The effect depends on the weapon yield to some extent and is greater for large-yield weapons.

C.4 ATMOSPHERIC BOUNDARIES

C.4.1 Cloud Albedo

The reflectivity or albedo of clouds is important in (1) determining

the amount of thermal radiation reflected out into space for bursts occurring above a cloud layer and (2) determining the amount of thermal radiation reflected back toward a surface target for a burst occurring beneath a cloud layer. Aldrich's[30] value of 0.78 as the mean value of the albedo of clouds applies only to California stratus clouds measured under rather similar conditions (thickness of about 500 feet or greater and occurring along the coast). Neiburger[7] has shown that for clouds of moderate thickness, albedo measurements could be correlated with theory,* but that, for thin clouds, the observations were considerably different from the calculated values. If a burst should occur in the middle of a cloud, half the scattered radiation would be directed upward and half would be directed downward.

Schmall[35] has considered the case of a burst beneath clouds for a nonscattering, nonabsorbing atmosphere by considering a receiver between two parallel Lambert planes (surface of the earth and the lower surfaces of a cloud layer). However, the atmosphere actually absorbs and scatters, and the surfaces are not true Lambert surfaces; hence, the results are approximate at most.

The problem of cloud albedo is compounded by reflections from the sides of a cloud and by reflections from upper layers that reach the ground by openings in the lower layers. The use of Tiros-satellite measurements of cloud albedo may become valuable for determining reflectivity of cloud layers for high-altitude bursts. It is doubtful whether more quantitative conclusions on cloud albedo will be reached in the near future.

C.4.2 Target-Surface Albedo

Target-surface albedos have been estimated for various features of terrain as reported by meteorologists under a variety of meteorological conditions; however, the angular distribution of reflected energy, especially for the 1% of the U.S. land mass occupied by cities, has not been measured. A representative list of conservative estimates of surface albedos is given in Table C.2. The effect of the variety of albedo values on the amount of thermal energy received at some nearby target fuel for the inhomogeneous conditions prevailing in urban areas has generally not been measured.

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* Hewson[5] states that cloud albedo is, in general, a monotonic increasing function of cloud thickness and cloud density and can range from about 0 to about 0.8 and that the reflection in clouds is relatively independent of the solar elevation angle if the transmission is defined for a horizontal surface both above and below the cloud.

TABLE C.2

Estimated Conservative Values of Albedo* of Various Earth Surfaces in the Absence of Fog[23]

Surface	Albedo (%)
Desert	24-38
Fields, various types	3-35
Forest, green	3-20
Grass, various conditions	14-47
Ground, bare	7-30
Sand, dry	18-28
Sand, wet	9-19
Snow or ice	46-90
Rough water, white caps	10-31
Water (average)	10
Shock-frothed water	40-80

* Albedo is defined as the fraction of the total incident radiant energy on a specified surface which is reflected.

Cahill et al.[31] have modeled six representative atmospheres in summer and in winter for three principal regions of the world: tropic, temperate and arctic. For purposes of their model, they assigned the following albedo values:

Region	Description	Albedo
Tropic	Land or ocean target surface	0.2
Temperate	Land or ocean target surface	0 or 0.2 (respectively)
Arctic	Snowfield target surface	1.0

Their choice is justified[39] in that most natural surfaces have albedos between 0 and 0.2, whereas snow and clouds have albedos approaching 1.0. No variation of albedo with time or location within each region is assumed in Reference 31.

Surface albedos vary with time and location because of a variety of parameters. The albedo of vegetation is somewhat dependent on changes in vegetation with season; however, since most cities have relatively little vegetation, it is doubtful whether the change in albedo is significant. The greatest variations of urban "surface" albedos result from meteorological parameters and in particular from snow cover, which, as estimated by Gibbons,[3] can alter the albedo value from 0.15 without snow cover to 0.75 with snow cover. The albedo for snow cover has been found to vary from 0.65 to 0.89 according to its freshness[3] and probably depending on population and industrialization. In addition, urban snow cover depends on the types of roofs, snow removal, and other parameters.

C.5 EXPRESSING ATMOSPHERIC TRANSMISSION[3]

C.5.1 General

From the preceding discussions, it is evident that the description of atmospheric transmission for all atmospheric conditions and for the possible weapon-yield and burst configurations is extremely complex. It is for this reason that a set of calculational rules that simplify the problem of estimating atmospheric transmission into several representative and practical cases was presented by Gibbons[3] and put into computer format by Martin.[40]

Gibbons' rules apply to atmospheric transmission for nuclear-burst fireballs at effective heights*, $h_T \leq 0.25$ mile, $0.25 < h_T < 10$ miles, and $h_T \geq 10$ miles for unclouded atmospheres and low surface albedos,

---

*h_T, the effective height (altitude above ground) for thermal radiation will generally be different than that for blast.

and for clouded atmospheres and other special cases. In order to determine which set of rules apply, the effective altitude of the fireball is determined as follows:

h_T for an air burst	$= h$
h_T for an above-surface but surface-intersecting burst	$= 0.7R$
h_T for a surface burst	$= 0.4R$

where h = height of burst point

R = fireball radius at second thermal maximum (See Eqs. C.11, C.12, and C.13)

C.5.2 Unclouded and Low Surface Albedo: $h_T \leq 0.25$ Mile

A quarter of a mile h_T was chosen because the lower atmosphere cannot be considered uniform through thicknesses greater than about 0.25 mile. Transmissivity for air bursts, above-surface but surface-intersecting bursts, and surface bursts for this case are found by substituting $K_1 = 2$ and $K_2 = 1.4$ in Eq. C.8. The effective slant range S_T is determined by the equation:

$$S_T = S_B - 0.6R \tag{C.10}$$

where S_B is the slant range from the burst point to the observation point P, and R is the fireball radius of the nonflat portion of the fireball surface at the time of the second thermal maximum.

The radius of fireballs for bursts up to 20-miles altitude may be calculated by the following:[40]

$$R\ (\text{air burst}) = 0.41\ W^{0.35}\ e^{0.0465h} \tag{C.11}$$

$$R\ (\text{surface-intersecting}) = 0.47\ W^{0.35}\ e^{0.0465h} \tag{C.12}$$

$$R\ (\text{surface burst}) = 0.53\ W^{0.35}\ e^{0.0465h} \tag{C.13}$$

where R = fireball radius (miles)

W = weapon yield (MT)

h = altitude of burst point above sea level.

The effective thermal partitions assumed[3] for use in conjunction with Eq. C.8 are as follows:

Air burst	0.33
Surface intersecting burst	0.27
Surface burst	0.21

Equation C.8 ($K_1 = 2$, $K_2 = 1.4$) is limited to $S_T < 45$ miles, which is the distance to the horizon at an elevation of 0.25 mile. If the visibility* is not known for Eq. C.8, the International Table of Visibility may be used as follows:**

Atmospheric Condition	Approximate Visibility (Miles)
Very clear	31
Clear	12
Light haze	6
Haze	2.5

C.5.3 Unclouded and Low Surface Albedo: 0.25 Mile $< h_T <$ 10 Miles

Gibbons[3] has found that Elterman's model[4] for a "clear standard atmosphere" (with haze component) can be employed to calculate transmissivity for any slant path by using optical thicknesses*** as given by Elterman for 0.65-μ radiation transmission neglecting "build-up."

*See C.3.1, for the distinction between visibility and meteorological range.

**Ref. 1, p.320.

***Optical thickness = σD or $\int \sigma(D)dD$, where σ or $\sigma(D)$ is the attenuation coefficient and D is the path length.

For a burst at an altitude of 10 miles or more, the calculated transmissivities correlate with those for luminous solar radiation; whereas for a burst at 0.25 mile, the calculated transmissivities correlate with those calculated by Eq. C.8 ($K_1 = 2$, $K_2 = 1.4$) on the basis of 12-mile visibility.

Transmissivities, T_c, based on Elterman[4] for 0.65-μ radiation and for effective thermal-radiation slant paths as a function of the effective zenith (incidence) angle of the fireball (Θ_T) and various effective fireball altitudes (h_T) may be calculated using the equation:

$$T_c = e^{-\tau(h_T) \sec \Theta_T} \qquad (C.14)$$

where $\tau(h_T)$ is the optical thickness for wavelength 0.65-μ of a vertical path from altitude h_T (10 mi $\geq h_T >$ .25 mi) to the ground surface.[4] It can be seen that T_c decreases for a given Θ_T as h_T increases. Also, for a given Θ_T, the decrease in the value of T_c as h_T increases from 10 miles to infinity is small compared to the value of T_c for $h_T = 10$ miles. Hence, the values of T_c for $h_T = 10$ miles may be used for estimating $T_c \geq 10$ miles. For $h_T \geq 10$ miles, this produces slightly high T_c values.

Precise values of T_c can be obtained by using the intermediate values of optical thicknesses given by Elterman.[4] The curve of T_c Vs. sec Θ_T for $h_T \geq 10$ miles (peak at 0.65 μ) is not much different from the curve of direct plus diffuse solar luminous radiation (range of 0.42 to 0.7 μ; peak at 0.556 μ) as given by Passell.[2]

For visibilities > 12 miles, T_c (other atmospheric parameters unchanged) would be greater than T_c for V = 12 miles, but situations where V > 12 miles are not common in urban areas. Moreover, Gibbons believes the effect on T_c by a moderate increase in visibility is not significant for S_T of much less than two mean scattering lengths, and hence for only a few of the possible burst geometries (for example, out to the 1-psi line for a 100-MT or a 1000-MT surface burst)[3] would T_c be significantly increased by a moderate increase in visibility (such as from 12 to 20 miles). Situations where V < 12 miles are ordinarily accompanied by heavy or light haze or fog and are determined as indicated previously.

C.5.4 Unclouded and Low Surface Albedo: $h_T \geq 10$ Miles

For reasons stated previously, all the attenuation between the fireball and any given ground surface point for bursts having an h_T greater than 10 miles, will occur in the lower 10 miles of the atmosphere.

Hence, the thermal transmissivity to a point on the ground from a fireball at a given zenith angle may be taken as the thermal transmissivity from a similar fireball at the given zenith angle and at an altitude of 10 miles.

C.5.5 Clouded Atmospheres and Other Special Cases

Gibbons[3] summarizes estimated values of a factor T', which is multiplied by the clear transmissivity T_c to give the effective overall transmissivity $\overline{T}$ for use with various types of cloud or haze layers.

Type of Cloud or Haze Layer	T'
Light haze	0.7
Medium haze (bright gray-white)	0.5
Heavy haze (dull gray-white)	0.3
Light cloud (sky light gray)	0.3
Medium cloud (sky dull gray)	0.2
Heavy cloud (sky dark gray)	0.1

Unless otherwise mentioned, these factors assume a low surface albedo and a receiver located with face normal to a line to the effective thermal source. For large zenith angles, T' will tend to be overestimated; whereas for small zenith angles, T' will tend to be underestimated.

The difficulties in modeling transmission through clouds and their reflectivity have been presented previously. For practical purposes, all burst-receiver geometries can be associated with one of the following fireball-atmosphere configurations:

1. Clear atmosphere.
2. Fireball below off-surface cloud layer or haze layer.
3. Fireball above off-surface or on-surface cloud (fog) layer or haze layer.
4. Fireball between off-surface cloud layer or haze layer and off-surface or on-surface cloud layer or haze layer.

If surface albedos are chosen simply as low (about 0.15) or high

(about 0.75) we are simplifying a complex situation. For additional simplification, we consider only the nearest approximately complete cloud or haze layer above the fireball and the nearest approximately complete cloud layer below it. If the fireball is partly above and partly below a cloud layer or haze layer, the two parts should be considered separate thermal sources.

Gibbons has summarized T' values for use with each of the above configurations (these values have been found in good agreement with the experimental results of Cantor.[17]) See Table C.3. Reference 3 should be consulted for further information on the use of T' factors and for additional factors which modify T'.

In summary, $\bar{T}$ as cited in C.2.3 (Eq. C.7 or C.8) may be obtained by determining T_c from Eq. C.14 in C.5 and multiplying it by T' from C.5.5 or Table C.3 for clouded atmospheres and other special cases.

TABLE C.3

T' Values for Several Fireball-
Atmosphere Configurations

Config. No.*	Surface Albedo	T'
1	Low	1
1	High	1.5
2	Low	1.5
2	High	2.25
3	Low	As given in cloud or haze layer chart for T'
3	High	1.5 times T' for corresponding low-surface-albedo case of configuration 3.
4	Low	1.5 times for T' for corresponding low-surface-albedo case of configuration 3.
4	High	1.5 times T' for corresponding high-surface-albedo case of configuration 3.

* Defined on p. 216.

APPENDIX C

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APPENDIX D

FUNDAMENTAL PROCESSES OF IGNITION AND COMBUSTION

D.1 TYPES OF IGNITION AND COMBUSTION

Most organic solids burn in air through a stepwise process of pyrolysis, volatilization, mixing of the volatiles with oxygen in the air, and the vigorous vapor-phase oxidation of the flammable constituents accompanied by the release of heat, part of which must return to the solid to maintain the pyrolysis reaction. Exceptions to these solids include materials that contain their own oxidants, such as solid propellants, (which are of very limited interest--if at all--to the subject of urban fire vulnerability) and materials that do not generate significant volatile products even at high temperatures, such as charcoal. The common case of pyrolysis followed by rapid oxidation in the vapor phase is usually accompanied by a buoyant plume of luminous gas, representing the region of diffusive mixing of fuel with oxygen and the zone of intense chemical activity called a flame. It is appropriate, therefore, to refer to this type of burning as flaming combustion.

The burning of volatile-poor fuels,such as charcoal, occurs when the surface of the solid reaches a temperature (about 600°C for charcoal) at which the solid itself begins to oxidize rapidly. In the case of charcoal, carbon is oxidized to carbon monoxide by oxygen, which diffuses to it from the air surrounding it. The CO can subsequently be oxidized to CO_2 as it diffuses out into the air. This type of burning is termed glowing or smoldering combustion. Since at least a large part of the heat of the first reaction (about 26 kcal/mol) is available at the surface to maintain the high temperature needed to sustain the reaction, the controlling factor in glowing combustion is the availability of atmospheric oxygen at the fuel surface.

The foregoing discussion implies that combustion is a steady (or at least quasi-steady) process that sustains itself as long as fuel and oxygen are available to one another and the heat release of the reaction exceeds the combined conduction, convection, and radiation heat losses from the reaction zone (pyrolysis plus oxidation). The transient process that initiates the steady process is called ignition. Ignition may be termed either flaming or glowing, depending upon which form of combustion it initiates, but it may be further classified as

(1) spontaneous or piloted, depending on whether it occurs as the result of heating alone or in the presence of flame or spark from an already-burning fuel, or (2) as sustained or transient, depending on whether burning continues after the external source of heat has been removed. This dependence on external sources of heat and other igneous agents makes ignition distinct from combustion.

D.2 FACTORS THAT GOVERN COMBUSTION BEHAVIOR

D.2.1 Fuel Composition

One of the main factors governing combustion behavior is the composition of the fuel. When heated sufficiently, most organic solids are readily converted to vapors through sublimation, melting and boiling, or decomposition, or a combination of these. Simple changes in state are not commonly experienced by the organic materials that are used in construction and furnishings and otherwise make up the bulk of the fuel load in urban areas. These materials are typically natural or synthetic polymers. They may soften or even melt when heated, but volatilization occurs entirely through decomposition. As a result, the composition of the vapors may bear little resemblance to the solid from which they originate, particularly when there is a carbon-rich residue (char) produced by the selective elimination of certain portions of the molecules that made up the original solid.

The commonest chemical constituent of the fuels making up the bulk of the fuel load of urban areas is cellulose. (See Appendix A.) As it burns, cellulose pyrolyzes to char (as much as a third to a half of the original weight) and a complex mixture of volatiles that, on the average, are correspondingly poorer in carbon (and to some extent hydrogen) content than the original solid was.[1,2] This highly oxygenated mixture of vapors and gases contains a considerable fraction of nonflammable constitutents (water and carbon dioxide). The main flammable constituents are the so-called tars, which are relatively high-molecular-weight compounds, including carbohydrates, furan derivatives, aldehydes, and (if lignins are present as in wood) aromatic compounds. The flammability of volatile products depends on the char-tar ratio produced by pyrolysis.[3,4,5,6,7] It has been known for some time that the presence of certain catalytic agents in cellulosic fuels will enhance the production of char at the expense of tar, which renders the fuel either less flammable or nonflammable.[3,4,8,9] This catalytic action is the principle on which many fire-retardant agents are supposed to work.[3,10]

Once the flow of volatiles stops or slows to the point where air can get in to the charred surface, flaming combustion gives way to glowing combustion. Glowing combustion may continue, develop into flaming combustion again, or go out. The reestablishment of flaming ignition can

occur whenever a fresh supply of volatiles appears. This recurrence will typically happen when uncharred material remains buried under a layer of char that is glowing with sufficient intensity (because of either the wind or the radiation from adjacent fuels) to supply heat by conduction to pyrolyze the buried fuel. Glowing combustion will not normally go out until the fuel is used up unless it suffers a severe oxygen deficiency or extreme heat loss, such as is frequently encountered in cases of isolated fuel elements.

It may be inferred from the foregoing that, in addition to composition of the fuel, some of the factors affecting the combustion behavior of solid fuels include (1) the heat of combustion, (2) the heat-conduction properties of the fuel, (3) the geometry of the fuel and the proximity of other burning fuels, and (4) the atmospheric environment in which the fuel is burning. Let us consider these one at a time.

D.2.2 Heat of Combustion

Heats of combustion of the commoner fuels in urban areas run about 4 to 5 kcal g^{-1} (7000 to 9000 Btu lb^{-1}).[1] Wood with a modest moisture content of, say, 12% or 13% by weight, has a heat of combustion typically ranging from 4.0 to 4.5 kcal g^{-1}, depending on the kind of wood and its resinous content. Cotton and paper-pulp products are about the same. Plastics (and other synthetic polymers) generally have higher heats of combustion ranging up to values of 10.3 kcal g^{-1} (18,500 Btu lb^{-1}) for paraffin and other petroleum products.[11] The heat of combustion of coal varies greatly, but typically lies in the range 6 to 8 kcal g^{-1} (11,000 to 14,000 Btu lb^{-1}). Considering the preponderance of cellulosic materials in most urban areas, a reasonable average value for the heat of combustion of urban fuels appears to be 4.5 kcal g^{-1} (8000 Btu lb^{-1}).

The rate at which the heat of combustion is released depends on factors remaining to be discussed. It should be mentioned at this point, however, that the heat released during the combustion of wood charcoal is 7.1 kcal g^{-1} (12,920 Btu lb^{-1}),[12] or about 1/3 to 1/2 of the total heat release of the original fuel. Since glowing combustion of wood generally follows the flaming process and lasts over a considerably longer time, this information is of some value in estimating the heat-release history of a single fuel element. Similar data are not available for paper products, cotton fabrics, and other thin fuels, but it is probably safe to say that a much larger fraction of their heats of combustion is released in a short period (during flaming) unless they have been treated with a flame retardant.

The moisture content of a fuel has some influence on the heat released during combustion, although it seems to be less a factor in the amount of heat released than it is in the rate of burning (and hence rate of heat release). It can, of course, determine whether or not a

fuel will burn at all. The heat of combustion of wood containing an equal weight of water is about 85% (Btu's per pound of dry wood) of that of the bone-dry material.[1] It is very difficult to burn wood with an equal weight of water in it, and even under the most extreme heating conditions, it is virtually impossible to burn wood containing twice its weight in water.

D.2.3 Heat-Conduction Properties

The heat-conduction properties of a fuel, as expected, have a marked effect on burning rate. If the rate of heat conduction into a thick material away from the surface is very high, the temperature of the surface and the material just under the surface, which is the source of volatile products, will be less than it would be for a material that does not conduct the heat away as fast. As a consequence, the rate of production of volatiles will be less, the flames will be feebler, and their contribution of heat to the surface will be less, which in turn will reduce the flow of volatiles. In the extreme, the burning rate will fall to zero. This behavior is normal for large pieces of wood when they lack external sources of heat.

The other extreme in heat conduction, materials with very low thermal conductivity, is not conducive to rapid burning either. Under such conditions, surface temperatures may be very high, but the amount of subsurface material that is hot enough to generate volatiles is severely limited by the inability of the material to conduct heat to it. In this case, an initially flaming fuel will cease to flame actively, but it may continue to burn by glowing combustion. The tendency of low-density materials, such as balsa wood, cotton linters, and punky wood, to smolder or glow rather than flame is probably due in part to their low thermal conductivity, although it may in some cases be an effect of extraneous contents such as mineral impurities.

D.2.4 Fuel Geometry and Proximity of Other Burning Fuels

Little of quantitative nature can be said concerning the dependence of combustion behavior on the properties and dimensions of a fuel element or on the spatial arrangement of fuel elements with respect to one another. Some qualitative ideas can be gained from observation of, and experience with, burning wood; these may be summarized as follows:[1]

1. Although a single large piece of wood will normally require heat from an outside source in order to continue burning, it will at the same time furnish heat to other pieces, mainly by its volatile combustibles burning at a distance from its own burning surface.

2. A local failure in air supply with continued application of heat results in charring without combustion, so that the volatiles do not

burn until they reach a more adequate supply of air.

3. Wood at a distance from the main combustion area may be heated by radiation to the charring temperature without combustion. In this case, the volatiles must reach ignition temperatures before they can be burned.

4. A spatial arrangement in which the combustion is explosive in character is the distribution of very fine, dry wood particles near enough to each other so that the combustion of one will ignite others and yet far enough apart so that each is surrounded by sufficient air for its complete combustion.

5. In a mixture of large and small pieces, the smaller ones may be entirely consumed with only superficial combustion of the large ones.

6. A very large piece of wood may be subjected to high temperatures for some time with only superficial combustion or charring. For this reason, a wooden beam may retain its strength properties under fire conditions that would cause the failure of a steel member.

7. When small pieces of wood burn in a plentiful supply of air, both charcoal and volatile combustibles burn about as fast as they are produced. Under other conditions (large pieces or limited air supply), the charcoal burns more slowly and much is left to burn by itself after flaming stops.

8. Since a good deal of shrinking occurs as wood is converted to charcoal, the surface of the charcoal is usually distorted and cracked. Glowing combustion will continue in these crevices long after combustion has stopped elsewhere because of the heat-conserving property of this configuration.

Although the foregoing list does not help much in analyzing fire behavior, it does give some feeling for the important parameters. For example, it seems clear that the surface-to-volume ratio is important, as are the compactness and distribution of large and small elements of a fuel bed. These are factors anyone who has successfully built a campfire knows intuitively, but the relationships are so complex that they have defied analytical description for a hundred years or more.

D.2.5 Ambient Atmospheric Environment

A reduction in the oxygen content of ambient air has a pronounced effect on combustion behavior. Solid fuels, such as wood, burn more and more slowly as the partial pressure of oxygen is reduced until at about 120 mm of Hg (16%), combustion stops even under the best of the other conditions. The presence of CO_2 or certain other gases (notably

halogenated compounds) increases somewhat the threshold oxygen concentration. One or more of these conditions may exist in an urban fire. Oxygen concentration may be reduced in an enclosure, whereas CO_2 and, in some cases, halogen compounds are products of fires in furnishings, finishes, and building materials.

The water-vapor content of the atmosphere has a significant influence on the burning rate of materials that absorb moisture. An example of the amount of moisture absorbed at equilibrium by wood is shown in Fig. D.1. Moisture contents do not generally exceed 20% even under conditions of very high relative humidities. Hawley[1] comments that wood with 10% moisture burns noticeably faster than wood with 20% moisture, but quantitative data are unavailable. Much the same situation exists with regard to the effect of air motion on burning rate. It is widely recognized that burning rate increases with increased air motion over the material (at least to a point--high winds can "blow a fire out"), but again only the grossest sort of qualitative information can be found.

For more detailed information on combustion behavior and the properties of fuels and environment that govern it the reader should consult the referenced literature.[1,3,5,10,13,14,15,16]

D.3 FACTORS THAT GOVERN IGNITION BEHAVIOR

D.3.1 General

The ignition behavior of cellulosic fuels exposed to intense radiant energy has been studied extensively because of its relationship to nuclear-weapons effects. Much of this work, therefore, has been done under conditions of greatest pertinence to the thermal-radiation aspects of nuclear explosions (high radiant flux levels and short thermal pulses), but, to a large extent, the information gained is relevant to the broader subject of ignition of organic solids by a variety of heat sources. Accordingly, we develop the subject here by first reviewing the state of knowledge generated by research in the field of ignition of cellulosic solids by thermal radiation and then discuss any unique or neglected aspects of the broader subject.

D.3.2 Ignition of Cellulosic Solids by Thermal Radiation

D.3.2.1 Basic Process

The ignition behavior of cellulosic solids by thermal radiation is governed by (1) the characteristics of the radiation; (2) the dimensions, extraneous contents, and optical and heat-transfer properties of the solid; and (3) the composition of the atmosphere surrounding the solid. In some cases, ignition behavior is also influenced by the geometry of

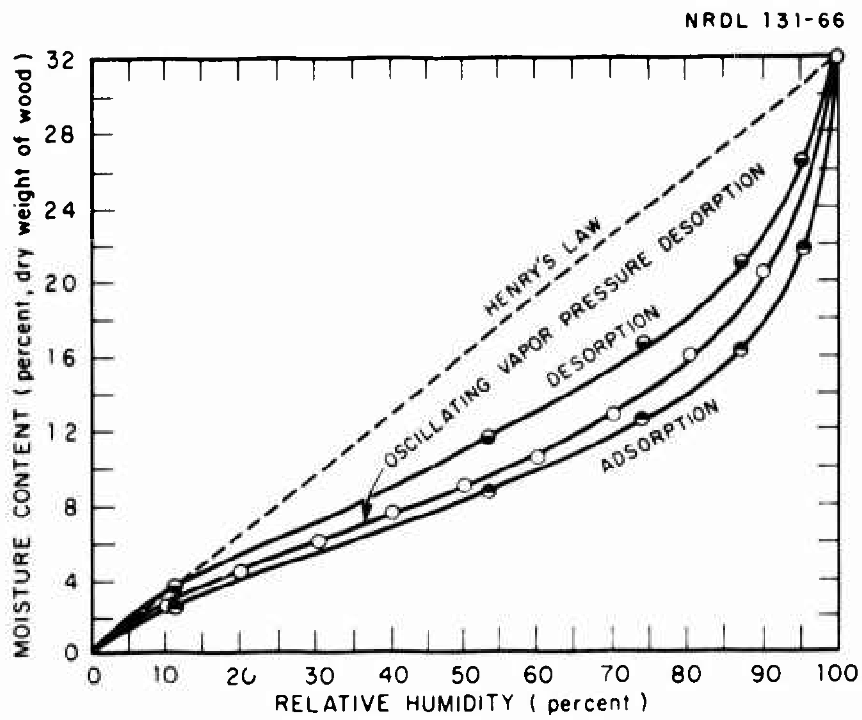

Fig. D.1 Moisture Content-Relative Vapor Pressure (or Humidity) Relationship for Sitka Spruce Under Normal Desorption and Absorption Conditions and Under Oscillating Vapor Pressure Desorption Conditions at 25°C*

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* A. J. Stamm, and W. K. Loughborough "Thermodynamics of the Swelling of Wood," Journal of Physical Chemistry, Vol. 39, p. 124, 1935

the solid and the motion of the air around the solid.

When a cellulosic solid is heated at one surface by a remote radiant source, the response can be described in one of three ways, sustained flaming ignition, transient flaming ignition and glowing ignition. These terms are chosen to indicate both the form of combustion initiated and whether or not combustion is self-sustained after the heat source is removed.

Spontaneous flaming ignition (initiation of either sustained or transient flames by a remote heat source alone) of a cellulosic solid occurs in the gas phase in front of the heated surface where the volatile products, generated by the local application of heat to the surface of the solid, mix with air under conditions amenable to the development of an accelerating rate of reaction between the fuel constituents and the oxygen of the air. Accordingly, a complete description of the process would include heat transfer, fluid mechanics, and chemical kinetics. In detail, consideration would have to be given to such factors as the deposition of heat in the solid and how the decomposition of the material is influenced by the transient temperature distribution, the diffusion of the volatile pyrolysis products, the mixing of the issuing volatiles with the surrounding air, the kinetics and thermochemistry of the oxidation reactions, and the combined heat losses of the system during the course of the ignition process.

Very often, however, in complex situations like this, much can be learned using an analytical model that does not attempt to consolidate all of the factors involved. The heat-transfer, fluid-mechanics and chemical-kinetics parts of the process can frequently be decoupled and individually scrutinized to discover which (if any) exerts the greatest control on the system under experimental study. A model based on the controlling mechanism (if one exists) will often correlate experimental data and reveal, in the nonideality of the incomplete model, the importance of missing factors. A large body of ignition data for cellulosic solids has been successfully correlated with parameter groupings derived from equations that describe the diffusion of heat into an inert solid. Two basically different approaches have been taken to achieve data correlation; both are briefly reviewed next.

D.3.2.2 Two Approaches to Correlating Ignition Data

Workers at the Joint Fire Research Organization (JFRO) in England have treated the ignition of wood using a mathematical model of an inert solid with Newtonian heat losses taking as a criterion for ignition the attainment of an "ignition temperature." For thermally thick materials, the ignition criterion suggested by theory is one of fixed surface temperature. The early work of Lawson and Simms[17] at JFRO indicated that transient flaming (spontaneous) ignition occurred when the temperature

of the exposel surface of wood reached 350 to 600°C, depending on the variety of wood. Subsequent work[18] in dimensional analysis of the thermal balance of irradiated solids has provided dimensionless groups that correlate, with fair success, experimental results for both spontaneous transient ignition and spontaneous sustained ignition. Empirically determined criteria are a fixed surface temperature of about 500°C for sustained ignition of thermally thin solids. These correlations break down completely for very low and high rates of heating.

The important parameters in the JFRO correlations are the thickness of the fuel, the properties of the fuel that control the diffusion of heat in the solid (conductivity, density, and specific heat capacity), the Newtonian cooling constant (a function of temperature), and the time-irradiance characteristics of the radiant pulse. Other parameters that must be allowed for are moisture content of the fuel, size of the area irradiated, external drafts, the absorptivity and diathermancy of the exposed surface (as determined by the spectral distribution of the source of radiation), and preheating. This latter group of parameters has been studied more exhaustively at JFRO than probably anywhere else in the world.

A similar approach to a generalized solution of the ignition problem began in this country about 1955 when Sauer[19] successfully correlated some preliminary ignition data for black alpha-cellulose (2% carbon content) exposed to constant irradiance (square-wave) pulses from a carbon-arc source (approximating a 5500° to 6000°K black body). In effecting the correlation, he chose to avoid specifying (or even introducing the concept of) an ignition temperature. The resulting correlation was quite simple in nature and yet remarkably successful except for low rates of heating. It treated only diffusion of heat into the solid and ignored chemical effects and heat losses. The success of the technique indicated that neither is important over a very wide range of exposure conditions. During the years since, the group at NRDL that cooperated with Sauer (and California Forest and Range Experiment Station) in the initial correlation program has adopted Sauer's basic tenets and has developed the correlation to a high level of precision and utility.

The final ignition behavior pattern (taken from Ref. 20) for square-wave exposure of black α-cellulose is shown in Fig. D.2. Note that, at small values of the Fourier Modulus (short times or thick materials), transient ignition occurs at the smaller values of radiant exposure and is followed at higher radiant exposures by persistent ignition. The threshold of spontaneous flaming ignition in this region is found to be independent of sample thickness. The threshold line is given by the expression

$$\frac{H\sqrt{t}}{\sqrt{k\rho c}} = \frac{H\sqrt{t}}{\sqrt{k\rho c}} \cdot \frac{\sqrt{t}/\rho c L}{\sqrt{t}/\rho c L} = \frac{Q/\rho c L}{\sqrt{k/\rho c}/L} = \frac{Q/\rho c L}{\sqrt{\alpha t}/L} = \text{constant}$$

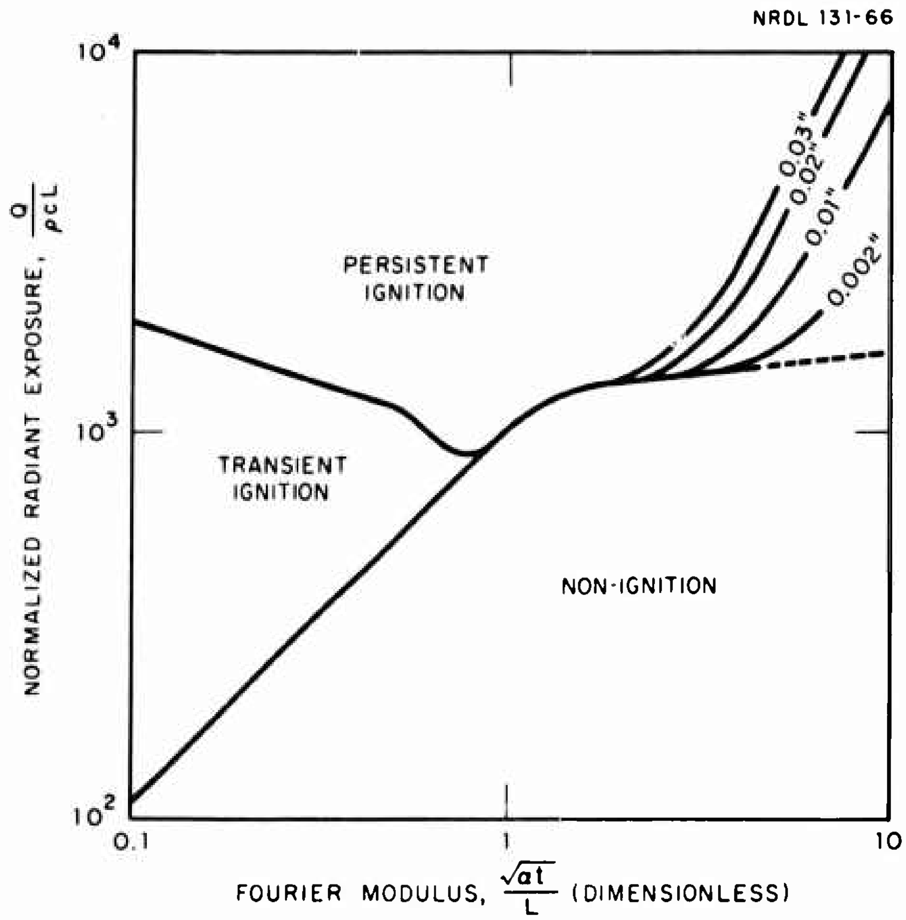

Fig. D.2 Ignition Correlation Pattern for Cellulosic Fuels

where H is irradiance, α = thermal diffusivity = $k/\rho c$, L = fuel thickness, t is exposure duration, k is conductivity, ρ is density and c is specific heat. This expression suggests that the criterion for ignition is the attainment of a constant high temperature at the exposed surface (estimated to be at least 600°C). Recent radiometric measurements by Alvares[21] indicate that the temperature of the exposed surface at the instant of ignition is between 600 and 650°C and is independent of the irradiance level and also independent of sample thickness as long as it is sufficiently great that no appreciable rise in back-surface temperature occurs prior to ignition.

At larger values of the abscissa, flames persist after exposures that terminate at the earliest appearance of flame. At still larger Fourier Moduli, flaming ignitions are frequently preceded by or entirely replaced by glowing ignitions. At this point, there occurs a transition from ignitions controlled primarily by diffusion of heat into the solid to ignitions governed by fluid mechanics; that is, convective heat losses and/or convective mixing of fuel and air become increasingly important in the process. For this reason, the correlation technique based only on heat conduction fails to correlate the data, and there occurs a separation into a family of curves for different thicknesses. These curves approach an asymptotic value of 0.5 cal $cm^{-2}sec^{-1}$, which is the critical irradiance as defined earlier. This asymptote may well represent the combined heat losses from both surfaces of a cellulosic sheet at a temperature that, for very slow heating, corresponds to ignition. Accordingly, this temperature would be about 300°C (for a 3/4-inch-diameter circular sample with surfaces vertical and having an emissivity of 0.9), which is in good agreement with measurements of ignition temperatures for furnace heating and the like.[22,23]

This value of "mean temperature for ignition" is significantly lower than the JFRO "fixed mean temperature" for sustained ignition of thermally thin solids,[18]. The NRDL-measured "surface-ignition temperature" for thick solids[21] is noticeably higher than the JFRO empirically derived value.[18] The JFRO "mean temperature" successfully correlates ignition data for a time-irradiance regime that is rather far removed from the regime of critical irradiance. As was mentioned earlier, the JFRO correlation breaks down for low rates of heating. But their critical-irradiance values agree quite well with the NRDL estimates, both in magnitude and insensitivity to differences between materials. This suggests that the "mean temperature" for ignition of thermally thin materials is not really constant, but rather a function of the duration (and hence rate) of heating.

The differences between values of "surface temperature" for ignition of thermally thick solids (500°C as empirically derived by JFRO, and 600° to 650°C as measured radiometrically by NRDL) may be the result, as Simms[18] suggests, of the smallness of the exposed area used in the NRDL experiment; but for the irradiance levels used, this explanation is not entirely

convincing. Perhaps, these differences indicate that it is not altogether wise to attach much physical significance to empirically derived numbers.

D.3.2.3 Ignition Behavior and Temperature Profiles

It is of some interest to attempt to interpret the ignition-behavior curves of Fig. D.2 in terms of temperature profiles attained during exposure. First, let us consider very short exposure durations: $0 < t < 0.1\ L^2/\alpha$, where L is thickness and α is thermal diffusivity of the exposed material. If the material is reasonably opaque, the energy is deposited in a very thin layer of material at the surface, which causes very high temperatures. The result is violent ablation, and ignition occurs almost instantly; but persistent ignition occurs only after the solid has suffered extensive ablation.

At the other extreme, for long, low irradiance exposures ($t > 4\ L^2/\alpha$), the material is (dimensionlessly) too thin to maintain a temperature gradient. The result is a uniform, low temperature that is slowly attained. The material is smoothly converted to char and often glows instead of flaming because it runs out of gaseous fuel (which is relatively poorly combustible anyway because of its high CO_2 and H_2O concentration) before temperatures rise high enough to induce ignition. As indicated earlier, ignition at long times depends on heat losses and certain, as yet ill-defined, geometric factors.

For intermediate exposure durations, the nature of the response is governed by thermal diffusion. Persistence of flames (or glowing combustion) at the end of the exposure depends on the thickness and volumetric heat capacity of the material. It is convenient to examine two cases. In the first case ($0.1 < \alpha t/L^2 < 0.6$), energy is distributed throughout the sample by conduction, which causes the unexposed surface to exhibit a small but finite temperature rise; but the exposed surface reaches the ignition temperature, say 600°C, before the average overall temperature is high enough (in excess of 300°C at least) to sustain the flow of volatile fuel. Clearly, if the temperature profile existing at the end of the exposure relaxes to a value of only 150°C, for example, the flow of volatiles will, for all practical purposes, stop and flaming will abruptly stop. Therefore, transient flaming is the threshold effect, and only after a somewhat greater radiant exposure will ignition be sustained.

In the second case ($0.6 < \alpha t/L^2 < 4$), the average or "relaxed" temperature of the material exceeds a value that is sufficient to maintain the flow of volatiles by the time the exposed surface reaches the ignition temperature and flames always persist. The major characteristics of ignition behavior can be explained, at least qualitatively, on the basis of the foregoing discussion.

D.3.2.4 Effect of Moisture Content and Optical Absorptance

Experimental work with α-cellulose containing varying amounts of carbon black in atmospheres of controlled relative humidity[24] clarified the influence of moisture content and optical properties on the ignition behavior. It was found that, for most kindling fuels (absorptivities of about 0.5 and higher), the ignition behavior is described by the correlation pattern of Fig. D.2 after allowance is made for the heat capacity of the moisture contained and by multiplying the radiant-exposure values by the radiant-energy absorptance of the material that corresponds to the spectral distribution for the appropriate source temperature. Therefore, to estimate ignition radiant exposures for a variety of cellulosic kindling fuels under a wide range of conditions, corrections can be readily applied to values computed for dry, black α-cellulose using the expression

$$Q_{a,m} = (1/a)(1 + 3.2m)\, Q_{1,0} \qquad \text{(D.1)}$$

where $Q_{a,m}$ is the radiant exposure required to ignite a cellulosic material having radiant-energy absorptance a (lying between about 0.4 or 0.5 and 1.0) and moisture content m (expressed as a fraction of the dry weight of the material), and $Q_{1,0}$ is the radiant exposure required to ignite cellulose having unit absorptance and zero moisture content. For more detailed information, the original reference[24] should be consulted.

D.3.2.5 Effect of Traces of Certain Inorganic Substances. It has been observed that traces of certain inorganic substances have a profound influence on both the ignition behavior and the thermal decomposition (pyrolysis) of cellulose.[7,8,9] Such substances appear to catalyze reactions whose main final products are char, water, and the oxides of carbon. These reactions in turn promote the glowing combustion of a radiantly heated cellulosic fuel often to the exclusion of flaming ignition. The process is not, as yet, well understood, but it is receiving considerable attention by Broido and co-workers[7] at the Pacific Southwest Forest and Range Experiment Station in Berkeley. This work may find application in ignition-countermeasures development.

D.3.2.6 Reliability of Radiant-Exposure Values for Ignition. Uncertainties in the values of integrated radiant exposure required to ignite black α-cellulose exposed to a constant irradiance are very small. To a high level of confidence, the values lie well within ± 10% of the central-tendency curves derived experimentally. Years later, ignition values can be reproduced, usually to within a percent or two, using the same material even if an entirely different source (such as an incandescent-tungsten source rather than a carbon-arc source) is used.* Moreover, the values are accurate in that all radiometric measurements are based

* Unpublished experimental work at NRDL.

on calibrations against the absolute, water-flow calorimeter.[25] Virtually as much can be claimed for less idealized kindling fuels, depending primarily on how well the required property values are known or can be estimated. Excluding plain white materials, materials containing significant mineral impurities and noncellulosic substances, such as wool and nylon, ignition values derived from the α-cellulosic ignition-correlation curves are probably good to better than 20%.

D.3.2.7 Factors Affecting Incendiary Threat of Nuclear Explosions. In the practical problem of evaluating the incendiary threat of nuclear weapon attack, numerous complicating factors must be considered before attempting to apply the results noted in the preceding sections. In addition to such factors as thermal-radiation attenuation by the intervening atmosphere, and the fields of view, distribution, and locations (relative to other combustibles) of the kindling fuels in a target complex there are complicating factors involving thermal-pulse characteristics of nuclear explosions, area and uniformity of exposure, and the geometrical complexity of real kindling fuels in "real-world" situations. The latter group of factors is the subject of the next discussion.

D.3.2.7.1 Exposure to Conventional Thermal Pulse. Experimental work in this area[26] was basically a repetition (though less extensive in scope) of the earlier NRDL measurements, but a thermal pulse designed to simulate the effective portion of the thermal pulse of low-altitude nuclear air bursts* was used instead of the square-wave pulse. The correlation necessarily had to be modified in one important respect. Since the duration of thermal pulses from nuclear bursts cannot be rigorously defined, it was necessary to use the time to peak irradiance in the Fourier Modulus. By the same token, the total radiant exposure is somewhat indefinite. Experimentally, with the laboratory-simulated pulse, the peak radiant power H_p, the time to peak power t_p, and the radiant exposure Q can be measured and are found to be related by

$$Q = \int_0^{10t_p} H(t)dt = 2.07\, H_p t_p \qquad (D.2)$$

However, the laboratory pulse does not include the long, low tail of the weapon pulse, which includes some 20% of the thermal energy. From field measurements we estimate the total radiant exposure to be

$$Q = \int_0^{\infty} H(t)dt = (2.6 \pm 0.5)\, H_p t_p \qquad (D.3)$$

* See Glasstone, S., (editor) Effects of Nuclear Weapons, U.S. Government Printing Office, 1962 edition, Fig. 7.91, p. 359.

Consequently, this difference should be borne in mind whenever attempting to apply laboratory data to weapon-effects problems. Because of the still unsettled state of scaling relationships, the only really reliable and generally useful weapon-pulse ignition data are those reported in terms of both H_p and t_p.

As anticipated, the ignition behavior for weapon pulses was found to be remarkably similar to that for square-wave exposure. Contrary to the case for charring of wood, however, no simple square-wave weapon-pulse equivalence was to be found. Qualitatively similar responses are observed when the weapon-pulse peak irradiance is roughly 3 times the square-wave irradiance level; thus

$$H_p/H = 2.7 \pm 0.2 \qquad \text{(D.4)}$$

but the weapon-pulse is significantly more efficient (20% to 40% less radiant exposure required) than the square-wave exposure for short exposures and significantly less so for long exposures.

From the resulting correlation, it is possible to predict the radiant exposures required to ignite a variety of kindling fuels under a wide range of conditions and over a wide range of weapon yields and burst altitudes knowing only the properties of the fuel and the appropriate altitude-weapon yield-t_p scaling. The job of measuring the necessary physical properties of every material of interest is not as formidable as it might at first seem, since the more difficultly measured properties, such as diffusivity, heat capacity, and moisture content, exhibit a regular dependence on such readily determined properties as thickness, weight per unit area, and the relative humidity of the environment.

A scaling equation, such as

$$t_p = 0.032 \sqrt{W \rho/\rho_o} \qquad \text{(D.5)}$$

where W is in kilotons, ρ is air density at burst altitude, and ρ_o is air density at sea level, can be used to extend ignition estimates to burst altitudes up to about 20 miles, but the higher-altitude estimates are not as reliable because of uncertainties in the air density-t_p scaling and because the thermal pulse may not be accurately duplicated by the laboratory pulse on which the estimates are based.

Aside from uncertainties introduced by possible simulation deficiencies, basically the same reliability can be attached to the experimentally derived curves for sea-level weapon pulses as for the square-wave pulses. Actual experimental measurements[27] made at the Naval Applied Science Laboratory (NASL) on black cotton sateen, newsprint, and pine needles using pulses simulating somewhat greater than nominal yield to 10-MT air bursts fall largely within about 20% of values computed from the α-cellulose correlation, although there are several values that differ by about 30%. It is noteworthy that the NASL values for black α-cellulose show variations from the NRDL values that are generally as great as those for real kindling fuels and that the values themselves are in all cases larger. The larger values may be due to the small spot size of the NASL source. The effect of exposure area is discussed in a later section (D.3.2.7.3).

D.3.2.7.2 Exposure to Pulses of High-Altitude Detonations. The current interest in the incendiary capability of high-altitude nuclear explosions has sparked a flurry of theoretical and experimental work directed toward the assessment of ignition behavior for very short pulses of very high radiant power. The previous lack of experimental data for these short exposures is due, in large measure, to the radiant-power limitations of simulation facilities. Megaton-yield weapons detonated at altitudes from about 30 to 60 kilometers are expected to radiate the effective portion of their thermal energy in times of the order of tens to hundreds of milliseconds. Anticipating radiant-exposure values for the sustained ignition of typical kindling fuels to be on the order of 10 cal cm^{-2}, we, therefore, expect to need irradiance levels on the order of 10^2 to 10^3 cal $cm^{-2}sec^{-1}$ to properly simulate high-altitude bursts of high-yield weapons. Carbon-arc sources, at best, provide irradiances extending only into the lower part of this range. Xenon flash tubes have the capability of very high radiant-power levels, but their pulse durations are generally less than 1 msec with a consequent inadequate radiant-exposure level.

Certain theoretical analyses indicated that for exposures of high radiant power, sustained-ignition thresholds would exhibit a very strong time dependence, and that they would rise precipitously to very high radiant-exposure levels as pulse durations are made increasingly shorter. For example, Siddons[28] used as a computational model a kinetically simple, first-order, chemically reacting system whose temperature history is given by the solution of the heat-conduction equation for an inert, opaque slab irradiated on one face and cooled convectively and radiatively at both faces. The threshold of sustained ignition was taken as that point where the volatile content of the material falls to some arbitrary low level. Despite the relative elegance of this model, it does not take into account surface ablation, and it calculates unreasonably high surface temperatures that lead to overestimates of radiation cooling.

On the experimental side, xenon-flashtube measurements made at NASL[29] showed no evidence of a sharp upturn in the ignition threshold for pulses intended to simulate MT-range explosions at about 75 kilometers. The flashtube pulse, which peaked at about 1 msec with an intensity of at least 1500 cal $cm^{-2}sec^{-1}$ and was virtually out by 10 msec, ignited closely printed classified pages of newsprint with a radiant exposure of 4.6 cal cm^{-2}.

Meanwhile, Martin[30] at NRDL extended the square-wave correlation for cellulose to smaller values of the Fourier Modulus (included in Fig. D.2) using a more intense carbon-arc source than was previously used, which provided useful exposures down to 20- or 30-msec duration. Ignition radiant exposures were found to retain their proportionality to the product ρcL while increasing less than a factor of 2 for an order-of-magnitude reduction in exposure duration.

Hochstim and McLain[31] at the Institute for Defense Analysis (IDA) obtained short-pulse ignition data from an ingenious Fresnel lens system which utilizes solar radiation. Their data generally support the NRDL results.

At the present time there is insufficient yield-altitude scaling information to permit detailed simulation of thermal pulses from high-altitude bursts (above 30 km). In fact, the information is so scanty that we can only guess at the suitability of currently available laboratory ignition data to the high-altitude problem. Our experience * is limited to the two high-altitude events of OPERATION HARDTACK, TEAK (megaton range, 76 km) and ORANGE (megaton range, 46 km) and two of the high-altitude, submegaton yield shots of the 1962 Pacific series, KINGFISH and BLUEGILL, whose burst altitudes were "tens of kilometers" above sea level. All of these bursts exhibited a single, brief pulse of thermal radiation indicating that the usual shock-formed air-opacity phenomena of low-altitude bursts are absent at higher altitudes. The most reliable evidence, however, indicates little change in thermal efficiency from the low-altitude case.

TEAK exhibited a very brief thermal pulse whose radiant power was greater and whose duration was shorter by some 3 orders of magnitude than that for the same-yield weapon detonated at sea level. One of the 1962 shots showed somewhat the same pulse characteristics, but because of the difference in altitude of the two shots, little can be said about the yield dependence of pulse duration. Some theoreticians propose a very weak dependence of duration on yield in this altitude regime. Xenon flashtubes appear to be reasonable sources for simulating pulses from weapons at these altitudes.

* Glasstone, S., ENW, pp. 676 and 677E, 1964 Revised Edition.

Shot ORANGE of OPERATION HARDTACK exhibited a pulse that was more nearly a square-wave pulse than a conventional thermal pulse, whereas the pulse of a somewhat higher explosion of the 1962 series was similar but decayed somewhat more rapidly. In view of the current state of uncertainty about pulse shapes from high-yield explosions in this altitude regime, we can conclude only that the ignition radiant-exposure values determined using 30 to 100-msec-duration square-wave pulses approximate roughly the ignition thresholds for megaton-weapon bursts at altitudes between, say, 30 and 60 km. Experimentally determined values for ignition of newspaper by 28 to 110 ms square-wave pulses[30] are displayed in Table D.1. Note that the values do not change drastically with duration in this range.

D.3.2.7.3 Effects of Exposure Area and Geometry. Laboratory exposures are necessarily idealized. Because of the limited area and depth of field of the uniform spot of most simulation facilities, laboratory studies are necessarily limited to flat samples of small exposure area (usually apertured) that are usually exposed with surfaces in a vertical plane normal to the optical axis of the source. This type of exposure ignores any possible influences of sample orientation, geometry, area, and nonuniform exposure. Hottel[32] has pointed out that, in the regime where diffusion-controlled ignition gives way to ignition governed primarily by convective heat loss, that is, for long exposures, the radiant exposures required to ignite materials like newsprint should depend on the area of the heated specimen. Measurements in a muffle furnace indicated to him that the temperature required for ignition rises as the heated area is decreased, which suggests a diluting effect in addition to increased convective heat loss for small specimens. Moreover, at a given temperature, small specimens were observed to glow, whereas larger specimens flamed. Taken together, these results indicate that the previous carbon-arc exposure results for long exposures tend to overestimate the radiant exposures for ignition and to predict glowing ignitions where flaming ignitions would in fact occur.

Our experience* definitely supports the latter indication, but it is not clear yet whether it is the result of increased area or of nonuniform irradiation. Simply removing the aperture from a given type of specimen frequently resulted in flaming ignition for an exposure that otherwise would have resulted in glowing ignition. Bending part of the sample back away from the spot or casting the penumbra of an opaque object on part of the exposure area causes the same result.

Recent unpublished studies** at both NASL and NRDL using large-area sources (banks of incandescent-tungsten, tubular-quartz-envelope lamps) show the same significant lowering of flaming thresholds (frequently down

* USNRDL Technical report on ignition, in preparation.
** Personal communication.

TABLE D.1

SQUARE-WAVE PULSE IGNITION VALUES FOR NEWSPAPER

Description	Irradiance (cal $cm^{-2}sec^{-1}$)	Duration (msec)	Radiant Exposure (cal cm^{-2})
Newspaper, darkest half-tone areas	50	42	2.1
	75	33	2.5
	100	28	2.8
Newspaper, gray half-tone	50	60	3.0
	75	40	3.0
	100	33	3.3
Newspaper, text areas	50	80	4.0
	75	60	4.5
	100	50	5.0
Newspaper, unprinted	50	110	5.5
	75	60	4.5
	100	55	5.5

to the previous glowing thresholds), but the lowest ignition radiant exposures fail to drop significantly below previously reported values; that is, critical irradiances for black α-cellulose remain at about 0.5 cal $cm^{-2}sec^{-1}$, and for newspaper, about 1 cal $cm^{-2}sec^{-1}$.

On the other hand, geometrically complex specimens (crumpled, wrinkled, folded, multiple sheets, etc.) have significantly lower ignition thresholds at long times of exposure than their plane-sheet counterparts. A loosely folded newspaper, for example, appears to have a critical-irradiance level of about 0.5 cal $cm^{-2}sec^{-1}$ compared to 1 cal $cm^{-2}sec^{-1}$ for a single sheet. This small difference in asymptotic value can have a major effect on estimates of ignition radiant exposures at long pulse durations. Figure D.3 illustrates the current estimates of ignition thresholds for newspaper as a function of weapon yield (modified by air density). The band represents estimated values for dark-printed, single sheets or for loosely folded or crumpled sheets with ordinary text printing. Moisture contents are those for relative humidities in the 40% to 50% range.

D.3.3 Ignition of Cellulosic Solids by Other Heat Sources

Cellulosic solids may be ignited by flames, hot gases, or hot solids in direct contact or any combination of these with or without accompanying radiant heating. The ignition of irradiated cellulosic fuels by momentary contact with flames, sparks, or firebrands can be evaluated from the results of piloted ignition experiments. Since ignition of this sort is relevant mainly to the subject of fire propagation, low rates of radiant heating are of primary interest. In fact, most of the experimental work has been done at irradiance levels near the critical irradiance. JFRO[17,33,34,35,36] has determined critical-irradiance values for a variety of materials with pilot flames in the gas-mixing region and on the exposed surface. These results show about a factor-of-2 reduction in the minimum irradiance level required for ignition when a pilot flame is present.

Weatherford and Sheppard[37] have theoretically analyzed and experimentally investigated the ignition behavior of cellulosic solids heated by high-temperature air streams in the virtual absence of radiation. The major contribution of this work is in revealing the unique features of ignition by convective heating, such as might be experienced in propagation of fire when flames or hot gases bathe an unignited fuel.

Their major effort has been given to recomputing, by a finite-differences method, the temperature profiles and rates of volatile fuel production in a mathematical model of heated slabs of wood originally proposed by Bamford, Crank, and Malan[38] and to a re-examination of criteria for ignition and sustained burning. They discovered that the thickness increments used in the Bamford, Crank, and Malan computations

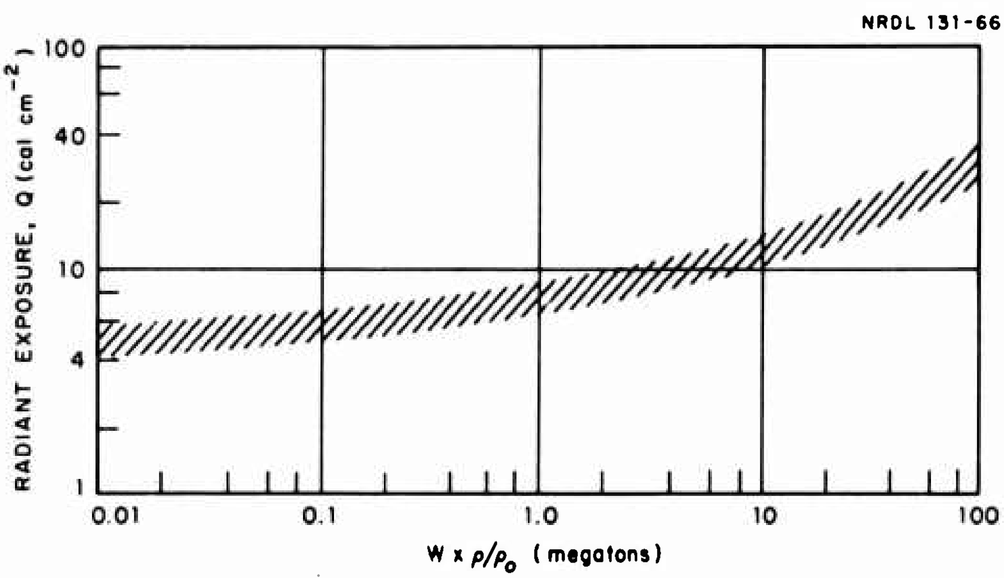

Fig. D.3 Ignition Threshold for Newspaper as a Function of Weapon Yield

were not thin enough, which gives rise to a situation of (computed) fuel depletion in one increment before significant vapor generation begins in the next. This computational defect, they conclude, caused unrealistic undulations in the computed rates of vapor generation with time and led to an erroneous supposition that the requirement for sustained ignition was the production of a specified vapor-generation rate of 2.5×10^{-4} g $cm^{-2} sec^{-1}$. The results of Weatherford and Sheppard[37] indicate order-of-magnitude differences in vapor-generation rate for conditions equivalent to the sustained-ignition thresholds of Bamford et al.

The results of the new computations provide graphical correlations of surface temperature and vapor-generation rates with time for convectively heated slabs (both one-sided and symmetrical two-sided heating) in terms of the temperature of the source and the initial properties of the slab (notably thickness, conductivity, diffusivity, and film coefficient). Vapor-generation rates were found to be nearly constant for given surface temperatures and source temperatures.

They noticed that the data of Bamford et al. have an approximately constant square of the Fourier Modulus (ratio of the product of heating duration and thermal diffusivity to the square of the slab thickness) and that this number corresponds approximately to the point at which the surface temperature of the slab departs perceptibly from that of a semi-infinite solid. To provide a definite and rigorously definable criterion, they propose the concept of a thermal feedback wave propagating from the center of symmetry in a slab heated on both surfaces or from the unheated surface of a one-side heated slab, and relate the threshold of sustained ignition to the arrival of the feedback wave to the heated surface. They find support for this proposed criterion in the agreement between the theoretical maximum thickness for sustained ignition of slabs with one-sided heating and that observed experimentally by Bamford et al. (approximately 0.3 cm for their conditions).

On the experimental side, Weatherford and Sheppard[37] measured piloted ignition times for hard board and alpha-cellulose using a convective heating source with temperature in the range of about 700° to 800°K. Their data were correlated on a basis derived from their theoretical work. They also correlated published ignition data of other laboratories on the same (or nearly the same) basis in an effort to discover similarities and to resolve differences in choices of ignition criteria. Weatherford and Sheppard combined the data of Bamford et al. with interpolated results of their own data (normalized to 800°K). The combined results show a distinctly similar pattern to the radiant ignition data of Sauer[19] and Martin et al.[20,24]

The final correlation (a Biot-Fourier correlation) shows that convective-heating ignition behavior is dependent on a Biot number parameter (ratio of the product of slab thickness and film coefficient

to the thermal conductivity of the slab material). For Biot numbers greater than about 1 (source temperature = 800°K), a transient threshold occurs; that is, flames flash from the pilot through the gases over the heated surface and persist as long as external heating is maintained, but die out if the heat source is removed. Bamford, Crank, and Malan[38] worked under conditions corresponding to Biot numbers between about 1 and 10, but were unable to observe this threshold, since they were bathing the slab with flame. If heating is continued, the threshold of sustained flaming is reached. Beyond this threshold the material continues to flame if both the pilot and heat source are removed. This threshold appears to have a constant Fourier number (about 0.3 for an 800°K source).

All of the data of Weatherford and Sheppard were taken at conditions of heating in the Biot-number range 0.1 to 1. As a result of normalizing to 800°K, however, their data overlap the lower Biot-number range of the earlier work. Their ignition responses can be described as (1) "sustained piloted flame after heat-source removal," and (2) "sustained piloted flame in presence of heat source." The latter satisfies the conditions of transient flaming if flames persist only in the presence of the heat source. On the lower Biot-number range (less than about 1 for a source temperature of 800°K), response (1) is the only form of ignition observed and the only form anticipated, since Fourier numbers of 0.3 or greater correspond to the first ignition threshold.

Weatherford and Sheppard conclude that the first appearance of flames over the convectively heated surface of a cellulosic slab, in the presence of a pilot, coincides with the occurrence of a relatively constant surface temperature and, more importantly, with the attainment of a minimum rate of volatile production. (They do not quote values, but from their paper, it appears that these values are about 500°K and between 1 and 10 g $cm^{-2}sec^{-1}$ for an 800°K source.) Finally, they conclude that, in addition to the foregoing requirement for flaming ignition, sustained flaming will occur only when the temperature profile in the slab has established itself to a level where it is "self-stabilizing (relative to its behavior upon heat-source removal)."

D.4 MECHANISMS OF FIRE PROPAGATION

D.4.1 General

Fire propagates through a solid-fuel complex through a series of events that include both ignition and combustion. In a continuous fuel element, the process is a steady, continuous one in which it is frequently difficult to define the line of demarkation between ignited and unignited fuel. The unignited fuel is heated to its "ignition point" by conduction, convection, and radiation of some part of the heat of combustion of the burning fuel. The relative importance of each mode of heat transfer will depend on factors considered below. In a discontinuous fuel array,

conduction plays no part at all. For large separations or generally downward propagation, radiation is the dominant heat-transfer mechanism, but fires can propagate by convection heat transfer or by convectively translated, burning solid-fuel elements, commonly referred to as firebrands. Propagation through discontinuous fuel arrays occurs in a series of discrete events; there is a clear distinction between ignited and unignited fuels, and the instant of ignition is a well-marked point in time.

D.4.2 Heat-Transfer Mechanisms

As a solid-fuel element burns, the heat generated by the reactions is transported away from the high-temperature region in several ways. From the flame zone, heat is radiated as governed by temperature and emissive efficiency of the flame. Flames originating from the gas-phase oxidation of the pyrolysis products of cellulosic solids (and most other solid fuels as well) are highly luminous and radiantly emissive because of the high concentration of solid particles, some of which may be derived directly from the solid fuel, but mainly are due to soot-forming reactions favored by the oxygen-deficient conditions of diffusion flames. In addition, a significant fraction of the energy radiated appears in the near-infrared emission bands of water and carbon dioxide. Energy radiates from the flame zone in all directions. Some of it (a small part in general) radiates back to the solid fuel which supplies the volatile fuel. Some radiates to unignited fuel where part of it is absorbed by the fuel (which raises its temperature). The remainder radiates to the noncombustible surroundings. In considering fire propagation, it is the amount of heat absorbed by the unignited fuel that we are concerned with. This amount is determined primarily by geometric factors. In general, the closer the unignited fuel is to the flame (and hence, the greater the solid angle of the field of view of the unignited fuel subtended by the flame), the greater will be the radiant-energy contribution. Other factors include the emissive power of the flame, its spectral distribution, and the effective absorptivity of the fuel.

The remainder of the heat of combustion in the flame zone (a large or even dominant fraction) is given up to its immediate surroundings by the direct transfer of kinetic energy of molecular motion. The flame imparts its energy to the air through a complex process of turbulent-eddy and/or laminar-diffusive mixing with air, along with collisional deactivation and redistribution of kinetic energy in translational, vibrational, rotational forms.

If the buoyant plume of air, burning gases, and/or combustion products encounter a solid object whose temperature, on the average, is less than the local temperature in the plume, heat is transferred to the surface of the solid through a quiescent layer (or film) of gas on the surface to the surface and subsequently into the solid by molecular

conduction. The rate of diffusion of heat into the solid in this manner is governed by a variety of interacting parameters including the gas-phase velocity profile, the temperature gradient (which in turn is dependent on the motion of the gases, their heat-transfer properties, the heat-transfer properties of the solid, etc.), the surface characteristics of the solid, and the flow of decomposition products (if any) from the solid. The usual approach to problems of this sort is to resort to an empirically determined film coefficient rather than to attempt a detailed analysis in terms of the large number of abstruse factors involved. The work of Weatherford and Sheppard,[37] already alluded to, is a good example of this. The convective transfer of heat from flames to solid objects is, of course, a salient factor in fire propagation.

Once active pyrolysis ceases in the burning fuel (because of either depletion of volatile-generating components of the solid or insufficient feedback of energy from the flame zone), combustion is limited by diffusion of oxygen to the air-fuel interface and occurs at or very close to the surface. The temperature of the glowing surface will typically run to 900°C (or even higher with a forced draft). The charred surfaces of organic solids are optically opaque and exhibit high emissivities (though there is a tendency toward diathermancy to, and reduced emissive efficiency of, the lower frequency photons of the infrared region). In consequence of the high temperatures and good radiating properties of solids undergoing glowing combustion, a very large share of the energy that escapes the combustion zone is in the form of radiation: as much as 3 cal sec^{-1} from every square centimeter of area of the surface distributed in wavelength as a nearly black-(or gray-) body spectrum which peaks around 2.5μ with approximately 95% of the energy at wavelengths shorter than about 1.2μ. Thus, the glowing solid fuel is a much more efficient radiator than the flames it fed at an earlier stage in its combustion. Probably 80% to 90% of the heat losses from the glowing solid are by radiation, though convective losses become increasingly more important as the speed of the air motion around the glowing solid is increased.

A significant fraction of the heat released in the combustion zone is conducted into cooler regions of the solid fuel or into other fuel elements in contact with it. The role of conducted heat in fire propagation is probably not important in most instances, since it is a relatively slow process compared to other propagation mechanisms. Conduction unquestionably is important, however, in penetration of fire through barriers, such as the walls of a room, for example. This is treated in more detail in Appendix F.

D.4.3 Mass-Transfer Mechanisms

Mass-transfer mechanisms that play a part in fire propagation can be classified as follows: (1) flow of hot or burning gases; (2) translation of burning solids, and (3) flow of burning liquids, e.g., gasoline flowing downhill.

The first class is inextricably connected to convective heat transfer and has been discussed briefly in D.4.2. A myriad of factors with complex interactions prevent first-principle generalizations. Empiric estimates can be made with modest reliability for a variety of cases using parameters that grossly describe the system (for example, dimensions of heat source and environment, rate of heat release, ambient fluid motion, and buoyancy properties of the fluid).

Firebrands, glowing embers, sparks, and other burning solids can be translated from the fire to unignited fuels by (1) falling under the influence of gravity, (2) being forcibly ejected by the explosive release of hot gases, and/or (3) being lifted away by the buoyant action of the fire. The probable relative ranges of these modes of translation increase in the order given, under most circumstances. Only rarely will burning pieces of a fuel complex tumble or roll to a distance greater than the height of the burning complex. The slope of the surface (ground or floor) is obviously a factor here. Explosive ejection can be of two forms, differing in scale. Moisture and pyrolysis products trapped in cells or voids in the fuel proper or between fuel elements can, on their release, carry relatively fine solid particles up to a few feet away from the fire. (These same particles are frequently the ones carried aloft by buoyant forces.) Rupture of containers of compressed gases at high pressure, as well as the detonation of explosives and other extremely rapid-burning fuels that may be contained within a burning structure, can throw relatively massive burning pieces of material for hundreds of feet. Burning solids carried up from the fire by buoyancy can range from the tiniest of sparks to massive construction members and will travel anywhere from a few feet to a few miles, depending on the intensity of the fire from which they originate and the wind structure above the fire.

The only published and generally disseminated information on transport mechanisms of burning solids up to the time of this writing is that of Tarifa et al.[39] They experimentally determined the changes in aerodynamic drag and the losses in weight, both as functions of time and wind speed, of spherical and cylindrical firebrands of several varieties of wood. They found that firebrand flight paths can be estimated, in all practical cases, by assuming that their flight paths are directly related to their terminal velocities of fall. With this simplification and the experimental data, Tarifa et al. were able to calculate flight paths for two different convection models; vertical and inclined convection columns of

constant velocity in a constant horizontal wind. These calculations show that even small spherical or cylindrical brands can reach very great horizontal distances while still burning if they leave the convection column and are picked up by the horizontal wind before they reach a certain critical height. The distances to which hazardous concentrations or still-burning firebrands are carried depends heavily on the inclination of the convection column and therefore on the horizontal wind velocity.

Additionally, the distance depends upon brand size and shape, convection velocity, and the species of wood of which the firebrand is composed. Neither the moisture content of the wood nor the spinning or tumbling motion of the brands exerts much influence on the flight paths. Similar measurements and calculations should be made on firebrands of other shapes. Given sufficient information about convective velocity profiles above free-burning fires, wind conditions with distance and altitude, and the number, sizes and shapes of firebrands produced with time, a very reasonable estimate of the fire-propagating potential of the firebrands generated by a large fire could probably be obtained. Before this state-of-the-art will be realized, however, considerable work remains to be done.

APPENDIX D

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APPENDIX E

FIRES FROM CAUSES OTHER THAN THERMAL RADIATION

E.1 SECONDARY AND TERTIARY FIRES

Approximately one-third of the energy yield of a nuclear explosion (below ~50 miles altitude) appears in the pulse of thermal radiation; and this energy, if absorbed by combustible materials, can ignite fires over a considerable area surrounding the burst point. The remaining two-thirds of the weapon energy must also be considered as a possible cause of fires, even though the forms in which this energy appears may be inappropriate for heating materials to their kindling temperatures directly. In addition it is likely that, in the disorder following a nuclear attack, the accident rate will be many times higher than normal; such incidents may also result in a number of fires. Fires that occur as a direct result of various nonthermal weapon effects have been referred to as secondary fires; similarly, fires resulting from human activity in a nuclear-attack situation may be termed tertiary fires.

These effects are discussed in the following sections. Since blast represents the major fraction of weapon energy (about one-half for low-altitude bursts), it is given primary attention. Other weapon phenomena and indirect causes of fire are discussed more briefly.

E.2 BLAST-CAUSED FIRES

E.2.1 General Description

The blast wave from a nuclear weapon, in contrast to the thermal pulse, cannot ignite combustible materials directly; its effect is rather mechanical displacement or disruption of objects in its path. (The air behind the shock front is at a higher temperature than ambient, but beyond a few fireball radii from the burst it will not be hot enough to cause ignitions.) In order for a fire to result, combustible materials displaced by the blast wave must come into contact with a source of energy, one either present initially (such as heating or cooking fires), created by the thermal pulse (primary ignition), or produced by the blast wave itself (for instance, shorted electrical wiring).

The analysis of the probability of such an event is more complex than the corresponding analysis for primary ignitions. The relative importance of primary and secondary fires from a nuclear explosion was not greatly clarified by surveys of the results of operational nuclear explosions on Japan.[1,2] Granted the limitations of these studies, however, much useful data can be derived from them. Other sources of data on secondary-fire mechanisms and incidences are investigations of conventional (high-explosive) bombing in World War II, industrial explosions, and earthquakes. Conclusions drawn from these studies are discussed in E.2.5 and E.2.7.

E.2.2 Secondary-Fire Mechanisms and Hazards

The sequence of events observed some distance away from a megaton-size nuclear explosion consists of a brief thermal pulse (plus some gamma and neutron radiation) received within a few seconds after detonation, followed a short time later by the arrival of a shock wave. Since the shock front propagates at a velocity far slower than that of the thermal radiation, it arrives at all but the shortest distances from the fireball after practically all the thermal pulse has been emitted and received. Passage of the shock front is accompanied by a nearly instantaneous rise in atmospheric pressure and wind velocity, followed by a gradual fall to ambient levels.

Structures can be damaged by blast in three ways: crushing by the higher than ambient pressures behind the shock front; displacement by wind and by the momentary pressure differential across the structure as the blast wave passes; and impact by missiles picked up and accelerated by the blast winds. In the region of severe blast damage, exterior and interior walls and the utilities built into them will be disrupted, applicances may be damaged by falling debris, and containers may be punctured by missiles or ruptured by being thrown against a wall or floor. Flammable materials and energy sources normally separated and insulated from each other may thus come together and start a fire.

The amount of energy used by typical American residences for heating, cooking, lighting, and powering appliances is considerable--quite enough, in fact, to cause the destruction of a residence by fire or explosion under the right conditions. Moreover, parts of these systems are particularly susceptible to blast damage (for example, gas pipes and electrical wiring passing through walls).

The possibility of widespread destruction resulting from a common household fuel is well illustrated by the account given in Ref. 3 of the Brighton, N. Y., catastrophe of 1951. Gas leakage caused an explosion in an underground vault containing pressure regulators that fed

natural gas from a pipeline to the distribution system for a section of Brighton. The regulator valves were forced open, which allowed high-pressure gas (at ~ 30 psi) to flow directly into low-pressure lines intended for gas pressures of ~ 1/5 psi. Homes served by these lines had no individual regulators or emergency-relief valves installed for protection.

"The effects of excessive pressure on the low-pressure system.... were sudden and disastrous. In many cases, where burners of pilot lights were in operation, torch-like flames roared up to a height of two feet or more. Some stove burners lighted, though the gas was shut off. In other cases the surge of pressure extinguished the pilots and allowed unburned gas to escape. Flame came out of automatic water heaters and completely enveloped the tanks, and in some instances ignited the floor rafters. Furnaces, which were shut down because of the mild weather, flared into life. In one case, fire first destroyed the heater, then ignited the basement ceiling above it....

"A few minutes after the failure of the regulators, the first home exploded.... At short intervals thereafter other houses throughout the area were shattered by explosions which in most cases completely demolished the buildings.

"Fire broke out in the splintered debris of many of the demolished buildings and, extending to adjacent dwellings, caused much additional damage.... Still other fires resulted from the abnormal operation of gas appliances.

"No records are available as to the order in which buildings exploded or fires started, but they occurred in rapid sequence. Within an hour and a half, nineteen houses were totally destroyed, fourteen more were seriously damaged,... and at least eleven were damaged to a lesser extent."* (Approximately 1500 dwellings were served by the low-pressure system.)

Incredibly, only 2 months later a similar accident occurred in Louisville, Kentucky. A stone, which had found its way into the system during construction many years before, lodged in the seat of a regulator valve. The consequent overpressuring of gas appliances resulted in the outbreak of about 50 fires.**

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* Ref. 3, pp. 11, 15

** Ref. 3, p. 1

Although safety design of gas utilities has been improved as a result of these and other disasters, gas seems likely to contribute significantly to the secondary-fire hazard in areas where distribution lines and appliances are severely damaged by blast. Indeed, because of its widespread use in the United States, its ease of ignition, and its property of diffusing widely from any leak (so that any nearby energy source may cause ignition), natural and manufactured gas may consitute one of the most serious potential secondary-fire hazards.

In general, any easily ignited common fuel should be considered a possible source of secondary fires. Special attention should be given to liquid or gaseous fuels (which may flow or diffuse until they reach a noncontiguous energy source) stored or transported in containers that are vulnerable to rupture by blast or debris. The most common of such fuels in ordinary residences are those used for heating and cooking. Data derived from the Hiroshima and Nagasaki surveys indicate that heating and cooking systems were indeed the most important causes of secondary fires, making up 53% of the total. These data also indicate that the next largest number of fires, 37% of the total, were electrically caused. Similar figures were derived from a study of earthquakes.*

The relative vulnerability of U.S. and Japanese residences to secondary fires is not known. The average energy use from all sources is probably considerably higher in U.S. than in Japanese homes, and liquid or gaseous fuels may be more widely used here for heating and cooking. On the other hand, Japanese construction materials in use in 1945 may have been more combustible, and the wide use of open charcoal braziers may have constituted another unique hazard.

Some common energy sources and fuels, and the probable effects on them of blast, are discussed in E.2.3 and E.2.4. Probabilities of secondary-fire ignitions are discussed in E.2.5: Primary attention is given to residential rather than to industrial hazards, since residential units are far more numerous and widespread and thus may be expected to contribute the greatest number of secondary fires. However, the overall fuel loading of most residential areas seems to be insufficient to support development of a mass fire.**

E.2.3 Energy Sources and Blast Effects

Energy sources capable of igniting secondary fires include flames, heat, arcing and sparks, and chemical reactions. These sources may be present before detonation of the weapon or be initiated by the blast wave.

* Ref. 4, App. A-2, C-2
** Ref. 5, p. 49

E.2.3.1 Flames. Flames are continuously present in most modern homes in the form of pilot lights for gas or oil-fired furnaces, cooking ranges, and water heaters; in addition, the main burners of these units may be in use at a particular time. Other less common installations are wood-burning fireplaces and coal furnaces, which do not have pilots. It is possible that the blast overpressure and wind may extinguish pilot lights and larger flames, especially in regions of severe blast damage (where combustible debris could be thrown into contact with the flame). Some flames, on the other hand, may be protected from the blast wave (for example, those in basement furnaces and water heaters). Burning solid fuels (wood, coal) may be scattered but not extinguished.

Fires ignited by the thermal pulse (primary ignitions) are discussed elsewhere. The development of such fires, however, may be influenced by blast effects on nearby fuels.

E.2.3.2 Heat. Other sources of heat are available besides open flames. These include furnaces and associated ducts and flues, ovens and ranges, lighting systems, and appliances and power tools. Blast damage to electrical wiring and appliances can cause short circuits accompanied by resistance heating; it is also conceivable that some structural components of a totally demolished building may be heated by friction as the building collapses.

Near ground zero, noncombustible objects may be heated enough by the thermal pulse to ignite any combustible material they may subsequently contact. In Japan, solid material at ground zero probably attained a temperature of 3000 to 4000°C, and even 4000 ft away, there is some evidence that temperatures in excess of 1600°C were reached.* The corresponding thermal fluxes received at these locations were approximately (assuming a yield of 20 KT, burst altitude of 1850 ft, and a reasonably clear atmosphere) 150 cal/cm^2 and 25 cal/cm^2 respectively.**

E.2.3.3 Arcing and Sparks. Electrical short or broken circuits can cause arcing as well as heating wherever the system is damaged: at the power station, along high-voltage transmission lines, at step-down transformers, service lines to houses, wall wiring, light fixtures, or appliances. Circuit breakers and fuses provide considerable protection, but are not an absolute guarantee against continued flow of current through a damaged circuit.

* Ref. 6, pp. 325, 338
** Ref. 6, p. 262

Tests at the Nevada site in 1955 indicated that electrical utilities were fairly resistant to overpressures of up to 5 psi and dynamic pressures of 0.6 psi, although some utility poles and distributor transformers were blown down.* Typical wood-frame-construction houses were collapsed or severely damaged by such overpressures; thus, there is a possibility that electricity will continue to be supplied to demolished houses containing broken gas lines, ruptured oil tanks, or other combustible debris, or at least to nearby distribution lines if the exterior wall connection is broken.

Sparks may also result from static charges generated by friction. Nonelectrical sparks (actually tiny pieces of incandescent metal) can be produced when metal objects strike with sufficient force against anything hard.

E.2.3.4 Chemical Reactions. Fires from chemical reactions would include spontaneous combustion and hypergolic (self-igniting) chemical combinations. Such reactions may present a certain hazard in chemical laboratories and some industrial processes, but are not expected to be significant in causing residential fires.

E.2.4 Fuel Sources and Blast Effects

Combustible materials might be classified by function (structural, decorative, heating/cooking fuel, transportation fuel, etc.), or by physical state (solid, liquid, gas). The following discussion of common fuels divides them according to the latter method, the assumption being that the diffusivity or fluidity of a material strongly influences its probability of being ignited by nearby energy sources. Thus, among the easily ignited substances, gases would be expected to constitute the major secondary-fire hazard, with liquids second and solids third in importance.

E.2.4.1 Gases. Gaseous household fuels include natural or manufactured gas, containing primarily methane or hydrogen and carbon monoxide respectively and the liquified petroleum gases, primarily propane and butane. The latter are more common to rural areas and in any case are relatively insensitive to blast damage*, since they are contained in heavy steel bottles or tanks. Gases produced centrally and distributed through pipelines, however, may present a significant potential hazard.

* Ref. 6, p. 262
** Ref. 6, p. 269

Although some damage to gas utilities from ground shock may occur (see E.3.1) the underground distribution system is expected to remain relatively intact beyond 2 or 3 crater radii from a surface burst.* Where houses have been totally demolished, however, pipes that passed through or were built into walls will probably be broken. The central gas supply may be destroyed or shut off by emergency means, but the high-pressure mains or even the low-pressure distribution lines would provide a reserve volume that could continue to leak gas for a time.

E.2.4.2 Liquids. Flammable liquids include fuel oil, gasoline, and many common household fluids (cooking oils, cleaners, polishes, alcohol, etc.). Heating fuel may be stored in the basement in a fairly heavy sheet-metal tank. Oil could leak from broken connections, but major damage to the tank would probably require total collapse of the upper floors into the basement. Small quantities of other fluids, however, are stored in more fragile containers elsewhere, especially near the relatively heavy fuel and energy loadings of the kitchen.

Volatile petroleum products, such as gasoline, are not ordinarily stored inside a house, but an automobile in an attached garage can present an equivalent hazard. The energy sources in a typical garage are usually few (small light and power circuit, automobile battery, and possibly a waterheater flame), but the fuel loading may be relatively high (trash, papers, etc.).

Automobiles parked on the street or even in lots should not constitute an important secondary-fire hazard unless external energy sources are available (although the thermal pulse can ignite primary fires in the car's interior, to which fuel tanks ruptured by flying debris can contribute). Operation of vehicles, however, increases considerably the probability of secondary ignitions. The energy available is considerably greater (hot engine and exhaust, ignition system), and the chance of collision with other vehicles is high if drivers are temporarily blinded by dazzle or injured by flying glass. Automobile fires on freeways or even city streets are unlikely to spread to nearby buildings, and hence will be insignificant as far as mass-fire development is concerned; but they may block routes for fire control and emergency vehicles. The NFPA Handbook** reports the following: Of the nearly 1,000 automobile fires reported in Boston in 1 year, 90% of those not caused by smoking or matches resulted from leaking fuel or shorted or defective wiring; 60% of the motor-vehicle fires reported to the Interstate Commerce Commmssion occurred in connection with collisions; fires occurred in 2.3% of all accidents reported to the ICC.

* Ref. 6, p. 266

** Ref. 7, p. 20-48

Large storage tanks for gaseous or liquid fuels are quite likely to be involved in fire or explosion if close enough to the blast to be crushed or seriously punctured; the large quantities of fuel spreading over a large area would make the probability high of finding a pilot ignition that would set off the entire mass. The ubiquitous auto service station should also be mentioned. Although its underground gasoline storage tanks are well protected from blast, the aboveground pumps could be sheared off. It seems unlikely that much fuel would be spilled, but any resultant fire might create explosive conditions as fuel vapor from the storage tank mixed with air.

E.2.4.3 Solids. Solid fuels make up most of the fuel loading of typical residences, since wood is the most common construction material in the U.S. Even after total destruction by blast, however, it is expected that wooden structural members would be ignited with difficulty by stray sources of energy that would suffice to ignite, for example, fuel oil.

More easily combustible solid fuels include fabrics (drapes, upholstery, carpets, bedding, clothing) and paper (newspapers, magazines, books). Many of these materials are light enough to be scattered about by the blast wave.

Finely divided solids (dusts) have some of the properties of gases, are easily ignited, and can burn with explosive rapidity. Coal dust and sawdust are two obvious examples. According to the NFPA Handbook*, of 1,110 important dust explosions in the U.S. between 1900 and 1959, 65 involved coal and 146 wood dust. Over 400, however, involved dusts of grain, flour, feed, or cereal; thus, even a bag of flour could conceivably be a minor potential hazard.

E.2.5 Probability of Blast-Caused Fires

It is extremely difficult to predict whether any of the various combustible materials and energy sources liberated by blast damage will actually come together and result in a fire, although it is clear that the probability depends on the quantities of fuel and energy available and their properties, and on the degree of damage sustained by the structure.

Empirical studies of the Japanese atomic explosions, of British and German WWII bombing experience, and of earthquakes have provided some data on secondary-fire probabilities. An SRI report[4] has concluded that the probability of secondary fires in Hiroshima and

* Ref. 7, p. 6-47

Nagasaki was about 0.01 per 1000 sq ft of floor space in the buildings involved, that is, about one fire per 100 small buildings (of ~ 1000 sq ft each) destroyed by blast. As might be expected, the probability of fire was somewhat greater in combustible than in noncombustible structures, and was also greater in certain high-fuel-loading industrial structures than in residences. The variation was within a factor of 2 or 3, however. The probability was relatively constant with increasing distance from ground zero, in contrast to the probability of primary fires, which fell off sharply.

Roughly the same probabilities were found for secondary-fire production by conventional bombs and earthquakes. It is of interest to note that the sample of earthquakes studied indicated no important difference between American and Japanese cities in this regard (six U.S. and three Japanese cities were included in the sample).

E.2.6 Extent of Blast-Caused Fires

Although secondary-fire probability was found to be fairly constant with increasing range from the Japanese nuclear explosions, it would be expected to decrease eventually as structural damage from blast became less significant. A conservative estimate of the extent of secondary fires in a given type of structure, supported by evidence from the Japanese explosions, may be taken as the range of moderate blast damage for such structures (sufficient to crack or distort exterior walls and blow down interior partitions), with a smaller but indeterminate number of fires expected at greater distances. For wood-frame residential units, moderate damage is sustained at overpressures greater than about 2 psi. This over-pressure level occurs at a scaled range of $\sim$ 4200 $W^{1/3}$ ft for an optimum height of burst, and $\sim$ 2500 $W^{1/3}$ ft for a surface burst (for W in kilotons).* For a 10-MT weapon, these ranges are respectively 17 and 10 mi. from ground zero.

E.2.7 Relative Importance of Primary and Secondary Fires

A number of surveys have been made of the prevalence in U.S. cities of fuels that could be ignited easily by a thermal pulse. For example, Bruce and Downs[8] concluded that, in the cities studied, several dozen potential ignition points (thin fabrics and paper) existed inside an average home (depending on climate, type of neighborhood, etc.), and an average of at least several points in each home would actually be exposed to the thermal pulse of a weapon exploded over the city. The number of significant fires would probably be less than the number of ignition points, but primary fires would still seem to be

* Ref. 6, p. 139

about two orders of magnitude more prevalent than secondary fires at intermediate ranges (~ 2 psi radius). Closer to the burst point where the thermal pulse would ignite heavier fuels than those considered above, the number of primary ignitions would be even greater. Beyond the 2-psi overpressure range, on the other hand, primary fires could be started by a large-yield weapon on a clear day in a region where secondary fires would be insignificant. Thus, under favorable conditions primary fires should be considerably more important than secondary fires.

However, where an explosion occurs above thick clouds or many primary fuels are shielded from direct radiation by buildings or other topographical features, the range and number of primary ignitions may be reduced considerably. Secondary fires could therefore be the more important in a region beyond the reduced primary-ignition radius and within the 2-psi radius.

There have been speculations and some evidence to indicate that the blast wave arriving a short time after the thermal pulse might blow out many primary fires within a certain range of ground zero. Experiments intended to verify this have been inconclusive.* It should be remembered, however, that a firestorm did develop at Hiroshima, indicating that either (a) no significant number of primary fires was extinguished, (b) the number of secondary fires was in fact sufficiently large to contribute to the development of the firestorm, or (c) the extinguished area was not so large as to inhibit development of the firestorm and was subsequently engulfed.

E.3 FIRES FROM CAUSES OTHER THAN BLAST

E.3.1 Direct Causes

Other weapon phenomena besides thermal radiation and blast include ground shock, initial and residual ionizing radiation, and electromagnetic pulse. Of these, the most important potential cause of fire would seem to be ground shock. The damage mechanism would be similar to that of earthquakes, with a similar number of fires expected in equivalent damage zones. However, since a negligible fraction of weapon energy goes into ground shock for an air burst, and a relatively small fraction even for a surface burst, for aboveground structures the shock wave in air should be considerably more important than that in the ground.**

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* Ref. 9, pp. B-5 - B-14

** Ref. 6, pp. 280-281

The other factors mentioned should be quite insignificant as causes of fire. An electromagnetic pulse might induce surges in transmission lines or house wiring near the burst, but these surges probably would simply open circuit breakers and fuses. It is difficult to see how radiation could have any effect at all. Extremely high dose rates would be required to heat materials significantly or to catalyze or otherwise influence chemical reactions. Evidently, only the thermal pulse and the blast wave need be considered as initiators of fire.

E.3.2 Indirect Causes

The incidence of fires as a result of accidents will probably be greater than normal following a nuclear attack. Such accidents may either be initiated by the weapon itself (flash blindness, burns, blast injuries) or by psychological reaction to the attack (nonattendance or improper shutdown of equipment, diversion of operator's attention). The increase in accident rate is difficult to predict, but in any case, such fires should be much less numerous than those ignited directly by the weapon. According to the NFPA Handbook,* there are some two million fires per year in the U.S. from all causes (building, automobile and aircraft, grass and forest fires, etc.). Assuming that the number of fires is proportional to population, this is equivalent to an average of about 30 a day for a city of one million population. Even if accidents increased this number by two orders of magnitude, it would be negligible compared to the number of primary and secondary fires.

* Ref. 7, p. 1-23

APPENDIX E

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APPENDIX F

APPLICATION OF FIRE FUNDAMENTALS TO MACRO-SCALE FIRE PHENOMENA

F.1 GENERAL

The behavior of a fire basically depends on whether it is burning in an enclosure or in the open. This appendix treats briefly these two situations separately and then discusses the factors that appear to most significantly limit the spread of fire within an enclosure, from one enclosure to another, out of an enclosure into the open, and from fuel complex to fuel complex in the open.

The most common example of a fire in an enclosure is the burning of furnishings, finishes, and other combustible contents (including the walls themselves, in some instances) of a room in a building. We will direct our attention almost exclusively to room fires as typifying enclosure fires. Other types of enclosure fires, particularly if they appear to have a unique set of parameters influencing their behavior, are considered as their importance to urban fires warrants.

F.2 CHARACTERISTICS OF FIRES IN ENCLOSURES

F.2.1 Basic Fire Behavior

The unique characteristic of fires in enclosures is the dependence of their behavior with time, on the dimensions of the enclosure, and on the location and dimensions of openings in the enclosure. When a fire starts in a room of a house, it burns for a while without perceptible influence due to the enclosure (walls, ceiling and floor) and openings; one may neglect any negative sort of influence, such as a strong wind or rain. In other words, it behaves as though it were burning in the open with restricted meteorological conditions. But as it grows in size, its combustion products and the heat generated by combustion will accumulate under these conditions, while some (though small) part of the available oxygen is consumed. Without ventilation*, the fire will go out in time after burning an amount of fuel, which is determined by (1) the dimensions of the room,

* As commonly used to mean the circulation of fresh air about a fire.

(2) the kinds and distribution of fuels in the room, and (3) the location of the initial fire relative to the fuel distribution and the walls of the room. Even with adequate ventilation the fire may still go out, depending on the above factors except, in most circumstances, the room dimensions. With limited ventilation, the rate of burning may be reduced by both oxygen deficiency and combustion-product accumulation. As the degree of ventilation increases, the rate of burning is eventually determined by fuel availability and the accumulation and transfer of heat.

F.2.2 Experimental Work With Model-Room Fires

A considerable amount of experimental work has been done on fires in enclosures to simulate, to some degree, fires in rooms of buildings. A commonly used experimental model is the wooden crib in an incombustible box having a variable-sized opening on one side. Member laboratories of the Conseil International du Batiment are engaged in a series of such experiments. The National Bureau of Standards[1] (a member of this organization), has conducted full-scale room-size enclosure studies in which the controlled variables are fire load and window size. In these tests, radiation is measured within the enclosure and above the windows; temperature is measured within the enclosure; and rate-of-weight-loss measurements are made continuously throughout the tests.

The U. S. Forest Service[2] has reported on the behavior, progress, and effect of fire in a simulated dwelling room in which temperatures, air pressures, and the concentration of gases in a burning room were measured.

Japan's Building Research Institute[3] has conducted fire experiments with model rooms ranging in size from a small model room (40 cm long x 40 cm wide x 20 cm high) with single openings to 1/3, 1/2, and full-size model rooms having single openings of several sizes. These experiments indicate that fire duration can be established from window area and weight of fuel. In particular, they have shown that the relation between fuel and fire duration established in the U.S.[4] and in the United Kingdom[5] can apply to the traditional building with small windows, but that fire duration is too long and the temperature as a function of time is too low for the contemporary building with large windows.

Experiments at the Illinois Institute of Technology Research Institute (IITRI)[6] on full-scale and half-scale, model-room fires indicate the relative importance of a number of previously suspected but unevaluated factors in the growth and propagation behavior of fires in residences. The IITRI investigation generally neglected the subject of item-to-item fire

propagation and focused attention on flashover* behavior in rooms furnished with upholstered chairs, sofas, and beds and in which fire starts in at least one major item of furniture.

In the full-scale experimental rooms (12 x 12 ft floor area, 8 ft ceiling, and 48 inch high x 62 inch wide unglazed window opening), the time from ignition to flashover averaged about 18 min when the room was furnished as a living room and (although not statistically very significant) about 8 min when furnished as a bedroom. The extremes for 54 tests of the types tested were 4 min and 2 hr. Within 10 min after ignition, 20% of the test rooms had flashed; and by 28 min, over 80% had flashed. With few exceptions, the largest part of the flashover buildup time was for the initial fire on the upholstered surfaces (which seemed to persist only in joints and seams) to penetrate to the interior spaces of the furniture item.

The half-scale, model-room fires indicated that the behavior of fire buildup also depends on the insulating properties and combustibility of the wall coverings. The evidence strongly suggests that primary ignition of major items of stuffed, fabric-covered furniture in moderately sized residential rooms will probably result in flashover of the rooms within about 10 to 20 minutes of ignition if left unattended.

The IITRI program of experiments[6] has in addition considered the propagation of fire from room to room and through walls, floors, ceilings, corridors, and stairwells. Penetration times (the time for the flame to appear on the unexposed side) obtained for various structural components (barriers) were comparable to standard fire-resistance ratings. The time for flashover to occur between compartments of equal volume separated by these barriers has also been determined. Time to flashover is greater than the time to penetrate the above tested barriers. The ventilation a fire receives due to wind or air drafts was found to markedly enhance the burning rate.

As indicated earlier, ventilation is a very important factor in enclosure-fire-behavior. It will, under most circumstances, determine the maximum burning rate of enclosure fires unless open windows are either very large or arranged so as to provide cross ventilation, or until there is partial collapse (with rupturing) of the enclosure.

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* IITRI has defined flashover as the instantaneous spread of surface flaming of combustibles, due to heating and ignition of gaseous decomposition products.

F.2.3 Ventilation-Controlled Enclosure Fires

A great deal of experimental work has been and is being done on ventilation-controlled fires. Thomas [7,8,9] has made several significant contributions to the state of knowledge of enclosure fires and the influence of ventilation on their behavior. In a 1960 publication,[8] he reviewed the available experimental work to that date and showed how the burning-rate data may be correlated in terms of rate of air flow into the enclosure. He pointed out that air-inflow rate is approximately proportional to the product of the area of the opening (A) and (for rectangular openings) the square root of the height of the opening (H). He used this air-flow parameter, $A\sqrt{H}$, to correlate data of his experimental model with other reported data. The correlation shows that, for well-ventilated fires, the burning rate is independent of the opening into the enclosure and is governed primarily by the fuel-surface area. With reduced airflow, the burning rate becomes less dependent on fuel and more dependent on ventilation and, for relatively small openings, is proportional to the air-flow rate and independent of fuel surface area as long as there is an abundance of fuel. The mean value of the constant of proportionality (with window dimensions given in feet and burning rate in pounds per minute) was found to be 0.68, with the spread of data between slopes (burning rate vs air-flow parameter) of 0.5 to 1.5 lb min^{-1} $\text{ft}^{-5/2}$

The previously mentioned IITRI report[6] recommends a value of 1.5 lb. min^{-1} $\text{ft.}^{-5/2}$ for the ratio $R/A\sqrt{H}$ in the strictly ventilation-controlled regime, where R is the highest value of the burning rate observed for a given opening size. The IITRI investigators point out that burning rate in a room with a given opening increases, up to a point, with the amount of fuel supply and that it is not until that point is reached that the fire is truly ventilation controlled. They suggest that some of the data, considered by Thomas[8] to be for ventilation-controlled fires, were in reality influenced by inadequate fuel supply. Burning rates measured at IITRI for half- and third-scale rooms were in close agreement with the upper limit of the Thomas correlation. Burning times measured in the same experiments indicate a peak-fire duration of about 8 min. According to IITRI estimates, approximately half of the fuel was consumed during this period.

F.2.4 Well-Ventilated Enclosure Fires

The subject of well-ventilated fires is, quite naturally, of greatest pertinence to the discussion of fires burning in the open (discussed in F.3), but it should not be neglected in considering fires in enclosures. Some enclosure fires are well ventilated throughout their periods of action, and most (if not all) fires in rooms that progress beyond the fully

involved stage become well ventilated when they penetrate an outside door or a door leading to another vented enclosure, such as a room, hall, or stairwell; or burn through a wall, ceiling, roof, or floor. However, well-ventilated fires in enclosures do not necessarily behave in the manner of fires in the open.

The behavior of well-ventilated, partially enclosed fires is not as well understood as that of ventilation-controlled fires. It has been suggested[8] that the steady burning rate with good ventilation is proportional to the surface area of the burning fuel. For rooms with large window areas, most of the active combustion occurs within the enclosure, and as a result, the thermal energy radiated from the enclosure is limited by the window area; whereas, limited ventilation forces a significant portion of the active combustion to occur in the gases issuing from the window, and the resulting flames above the top of the window contribute to the thermal radiation emitted. On the other hand, the strong, buoyant convection forces of fires that have become well ventilated by penetrations that permit a generally vertical flow of air, cause flames to issue from roof areas or upper-story windows, which enhances their ability to spread the fire to nearby structures via radiant heating (not to mention convective heating and firebrand transport). The IITRI Phase III report[6] treats some of these matters in greater detail.

Experimental-model studies of well-ventilated enclosure fires have been conducted by Thomas[8] and Waterman et al.[6] using wood cribs in small, incombustible enclosures. The IITRI data for 3-, 6-, and 9-ft cubical enclosures (one side open) indicate that the burning rate is approximately 0.1 lb/min for every square foot of fuel surface area. Although not indicated, burning rate is undoubtedly a function of the kind of fuel involved.

F.3 CHARACTERISTICS OF FIRES IN THE OPEN

F.3.1 General

The subject of free-burning fires in the open covers a very broad spectrum of sizes and features, from bonfires to firestorms and from grass fires to oil-refinery fires, and includes, as a very important case in urban-fire considerations, the building fire from the point in time when the roof collapses.[10] Characteristics in common to all such fires are the dependence of burning behavior on meteorological conditions, the nature of their own convection column, and the density, type, and distribution of fuel. Here, we consider fires in the open: first, in terms of the behavior of an isolated free-burning fuel complex; second, in terms of spread of fire from one free-burning fuel complex to another; and finally, in terms of the interactions of two or more established

free-burning fires.

F.3.2 The Isolated Free-Burning Fire

Despite the large number of isolated free-burning fires every year, an appalling lack of information about them still exists. Several theoretical models of convection columns and air-inflow patterns have been developed, and each shows some degree of success in describing the gross features of free-burning fires. From these theoretical considerations, groups of parameters have been extracted to provide a basis for correlation of data on experimental fires.

P. H. Thomas,[9] D. Gross,[11] W. L. Fons,[12] T. E. Waterman et al.[6] have measured the flame heights and burning rates of wood cribs and correlated the data, with moderate success, using a buoyancy concept. The ratio of flame height to the dimension of a cubical crib have been shown to be a function of the dimensionless group, $R/\rho_o\, g^{1/2}\, D^{5/2}$, where R is the burning rate, ρ_o is the ambient air density, g is the gravitational acceleration and D is the crib dimension (length of cube). Since an isolated fire in the open is always well ventilated (unless, perhaps, it is a very large fire), the burning rate is determined primarily by the fuel surface area.

Southwest Research Institute (SwRI)[13] has demonstrated that scaling laws apply to actual models of structures as well as to wood cribs. Combustible models were made of a single type of fuel (hardboard of 1/8", 1/4", and 1/2" thickness) in 3-inch, and 12-inch cubes. The choice of cubes is a limiting factor in that the height was much larger with respect to the other dimensions than usually exists in buildings. Besides fuel thickness and characteristic dimension, other parameters incorporated into the models were two sizes of wall openings representing open windows, compartments connected by openings representing open doors, and a roof opening. During burning, weight loss and flame height were the most useful measurements for correlation. Ignited in a corner most of the models burned to the diagonally opposite corner. This difference in the burning behavior from that of crib fires probably is the reason that at the same burning rate (H/D vs. R^2/D^5, where H is the height of the model, D is the length of the model, and r is the burning rate)* crib flame heights were greater than the flame heights of the SwRI models of structures.**

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* The quantity $\frac{R^2}{D^5}$, which has the dimensions $gm^2\ sec^{-2} cm^{-5}$, appears in the equation derived from the dimensionless Froude number (velocity over length-times-gravity) by assuming the rate of burning to be directly related to the mass flow of the gas.

** Ref. 13, p. 12, Fig. 5.

F.3.3 Basic Processes of Fire Spread in the Open

Appendix D presents some of the more fundamental principles of ignition, combustion, and fire propagation. Here, we endeavor to show how these principles might be applied to the spread of fire through the kinds of fuel arrays commonly found in urban, suburban, and adjacent vegetated areas. We recognize two rather different cases being commonly encountered: (1) continuous fuel arrays, such as fields of underbrush, grass, or other vegetation, as well as docks, ramps, fences, litter, and other relatively unbroken arrangements of man-made fuels, and (2) discrete fuel arrays typified by structures and isolated concentrations of vegetation, such as trees. The process of fire spread through each is sufficiently different to warrant separate discussions.

F.3.3.1 Fire Spread Through Continuous Fuel Arrays Because of the proximity of the individual fuel elements, fire spread through continuous or nearly continuous fuel arrays is expected to be influenced to a large degree by convection. Considerable research has been devoted to learning how to describe fire propagation through relatively uniform beds of paper, pine needles, and similar fine combustible fuels; and numerous attempts have been made to mathematically model the process through heat-transfer relations. Radiation modeling is the most popular, though a few of the more industrious workers have struggled through the complex considerations of combined radiation-convection models. Hottel[14] has shown that complete modeling of the interaction between radiation and flow is impossible. Flow patterns are modeled by assuming that radiation is sufficiently small so that the flow pattern is not affected. Little headway has been made toward a genuinely satisfactory solution to this problem.

Fire-spread models that treat radiation from the flames over the burning bed as the governing factor have been the ones most commonly used. Their popularity is due to the relative ease with which they can be handled and to the intuitive expectation that the effect of wind on rate of spread is a result of enhanced radiation exchange between flame and fuel when the flame front is forced by the wind to lean over the unignited bed. Unfortunately, the evidence, which has been accumulating in recent years, indicates that radiation from the flames is not the governing factor in the spread of such fires. In fact, there is some evidence for concluding that radiation plays a relatively minor role when fire is spreading rapidly under the influence of wind. Measured fire-spread rates are too large to be explained on the basis of heating by flame radiation alone. Anderson and Rothermel[15] suggest that, in addition to radiant preheating of fuel by flames, important factors in the increase in rate of spread with wind are (1) the proximity of flames to the ignitable gases rising from heated fuel just ahead of the flame front and (2) in cases of high wind speeds, forced convective heating of the unignited fuel by lateral

motion through the fuel bed of hot gases from the combustion zone.

The importance of radiation from the glowing embers of the combustion zone should not be overlooked, at least for conditions of low wind speed. McCarter and Broido[16] found that the rate of spread through wooden cribs burning under still conditions was negligibly reduced by complete quenching of the flames above the crib or by shielding the unburned fuel from most of the flame radiation. For the conditions of this experiment, it appears that radiation from the burning solid dominates the propagation process.

Spread of a wind-driven fire in nearly continuous fuel beds appears to be dominated by a process of direct flame contact. Byram[17] has demonstrated the importance of direct flame contact in a series of laboratory-scale experiments of wind-driven fires. Without exception, his results show discrete propagating events occurring when flames contact an unignited fuel element; often, this resulted from random fingers of flame leaving the main flame zone at the point where vortex formation first appears. Although there is some uncertainty about how well such results can be scaled up to full-sized fires, there is little reason to reject such a mechanism as an important (if not controlling) one in wind-driven fires. Parameters on which this mechanism would depend include flame lengths, angles, temperatures, and eddy motions and their dependence on wind speed, burning rate (which in turn depends on a number of factors, such as wind speed, fuel loading and subdivision, and moisture content), and the dimensions of the burning zone.

Very little quantitative experimental work has been done to assess the relationships between fire-spread rate through continuous fuel beds and the multitude of parameters on which it depends. The recent work of Anderson and Rothermel[15] can be cited as a significant contribution to this subject and representative of the current state of knowledge. They studied the effect of moisture and wind on rate of fire spread through packed beds of pine needles and empirically derived a set of equations for predicting rates of spread in forest fuels. Their results show a linear dependence of spread rate on moisture content and either an exponential or power law dependence on wind velocity, depending on the kind of pine needles being burned.

The linear dependence of the experimentally measured spread rate on moisture is given by:

$$R_{m,o} = R_o - m\,\Delta R \qquad \text{(F.1)}$$

where $R_{m,o}$ is the rate of spread in still air through fuel having moisture content m (percent of dry weight), R_o is the rate of spread in

still air through dry fuel, and ΔR is the variation in the spread rate for every percent variation in the moisture content (m). The experimental values are listed in Table F.1.

This predicts a rate of spread in still air of about a foot per minute for dry pine needles and a zero rate of spread when the moisture content rises from 20% to 23%.

Combining these results with a previously established dependence of spread rate on the ratio σ (fuel surface area to fuel volume ratio) and the ratio λ (void-volume to total-fuel-surface area ratio which is the reciprocal of compactness) by Curry and Fons,[18] Anderson and Rothermel[15] derived the following equation for still-air spread in light forest fuels:

$$R_{m,o} = (\sigma\lambda)^{1/2} (R_o' - m\,\Delta R') \qquad (F.2)$$

In this expression, R_o' is the rate of spread in still air through dry fuel of equal compactness $(\frac{1}{\lambda})$ and surface to volume ratio (σ), and $\Delta R'$ is the change in rate of spread through that fuel for every percent change in moisture content (m). Values of R_o' and $\Delta R'$ are given as 0.272 ft/min and 0.012 ft/min, respectively. This relationship can hardly be considered established from the Anderson and Rothermel work, however, inasmuch as neither σ nor λ was varied appreciably.

TABLE F.1

Data From Anderson and Rothermel[15]

	Ponderosa Pine Needles	White Pine Needles
R_o	1.04 ft/min	1.12 ft/min
ΔR	0.004 ft/min	0.051 ft/min
m	4.4% to 9.9%	4.9% to 11.9%
σ *	1536 ft^2/ft^3	1980 ft^2/ft^3
$1/\lambda$ **	99 ft^2/ft^3	119 ft^2/ft^3
Relative Humidity	15% to 50% $\pm$ 1.5% ***	

* σ is the fuel-particle surface area-to-volume ratio.

** λ is the void volume divided by the total fuel surface area; its reciprocal $1/\lambda$ is the compactness.

*** Additional tests were run at relative humidities of 6%, 10%, and 75%.

Under conditions of wind velocity ranging up to about 8 miles/hr (700 ft/min), the ponderosa-pine needles exhibited a fire-spread rate that was exponentially dependent on wind velocity. Data taken at various wind velocities and fuel moisture contents fit the relationship:

$$R_{m,u} = R_{m,o} e^{u/r} \tag{F.3}$$

where $R_{m,u}$ is the rate of fire spread through fuel of moisture content m driven by a wind velocity u, $R_{m,o}$ is the rate of spread through the same fuel in still air, and r is an empirical constant (independent of moisture within experimental limits of measurement) having a value of 264 ft/min. This velocity corresponds to the wind velocity (3 mi/hr) that would increase the rate of spread by a factor of e; that is, every 2 miles/hr increase in wind velocity will approximately double the rate of fire spread through beds of ponderosa-pine needles.

For the white-pine needles the empirical equation was:

$$R_{m,u} = \left(1200 + 113m - 25.5m^2 + 2.35m^3\right)^{-1} u^{1.6} \tag{F.4}$$

where u is expressed in ft/min. This is a much less satisfying equation than Eq. (F.3) for ponderosa-pine needles and obviously cannot be used for very low wind velocities, since it predicts zero rate of spread in still air. This equation indicates that a 54% increase in wind velocity would double the rate of fire spread through white-pine needles, which suggests that fire will spread more rapidly through white-pine needles at low wind velocities; but at high wind velocities (extrapolating the results beyond the conditions of the experiment) fire in ponderosa-pine needles will spread faster than in the white-pine needles. No explanation is given in the report on the basically different behavior of the two fuels, which superficially appear to be quite similar.

The relationships of Anderson and Rothermel do not allow evaluation of a number of parameters that are required to generalize the behavior of fires spreading through continuous fuel arrays. Emmons[19,24] has proposed an appropriate fire-spread theory (see F.3.4.1) that might be used as a model for guiding future experimental work in fire spread through packed beds.

Under some circumstances, firebrands may dominate fire spread through continuous fuel beds. The small amount of information available on fire spread by brands has already been summarized in Appendix D (D.4.3).

F.3.3.2 Fire Spread Between Discrete Fuel Arrays When concentrations of fuel are separated by relatively large, fuel-poor spaces, the spread of fire is governed in large measure by radiant-heat transfer. Many of the factors that influence fire spread through continuous fuels (such as flame temperatures, rates of burning, and fuel density) are equally important to fire spread between discrete or discontinuous fuel arrays; but, in addition, there are factors peculiar to, or significantly more (or less) important in the process of fire spread between discontinuous fuel concentrations. The prime example of a discrete fuel array in urban areas is a building (residence, office building, factory, school, warehouse, etc). Types of buildings range from all-wood-exterior, frame buildings to reinforced masonry buildings. As radiant sources, they may be limited to an area not greatly different from their window openings, or they may radiate from their entire outside surfaces plus a not inconsiderable flame envelope above their roofs.

The literature on spread of fires from building to building has been comprehensively documented by Salzberg.[20] Based on this, the IIT Research Institute has developed a computerized fire-spread model[21] to permit evaluation of probable fire-spread behavior when radiation heating is the determining factor. Gutterman,[22] also of IITRI, has used many of the same assumptions in developing a simplified computer model for predicting the minimum expected fire damage to urban areas.

This model determines the lower bound to the actual amount of damage that would be produced. The basic way in which this is done is by applying the model to a block (approximately corresponding to the usual city block) and ignoring any fire spread between blocks. Fire spread within the block is characterized by assigning the block a priori to one of six fire-spread categories. Each category corresponds to a different assumption as to the way in which the fire will spread within the block. The application of engineering judgment to the information concerning construction type of buildings within the block and the geometric arrangement of buildings is used to assign a fire-spread category to the block.

From a specific burst location, ignition probabilities are computed for each story of each building. These are combined by a formula depending upon the fire-spread category of the block to give the expected percentage of stories in the block that are destroyed by fire. This is the quantity used for expected damage to the block. Modified U. S. Census Bureau descriptions of urban areas are used (applicable for single and multi-burst cases) in this model for fire-damage analysis.

In Salzberg's computer model,[21] it is assumed that the flames and other intensely radiating areas of the burning building (such as windows) may be represented by a 1600°F (871°C) source temperature and that a reasonably steady irradiation flux of 0.8 cal cm^{-2} sec^{-1} will ignite

fuels in adjacent buildings spontaneously if there is no wind, or if the wind is toward the burning building. Radiant fluxes as low as 0.4 cal cm^{-2} sec^{-1} will ignite fuels in downwind buildings if the wind is strong enough to carry flames, sparks, or brands to serve as pilots to ignite the already heated fuel. The remaining factors necessary for the analysis are the radiating areas of burning buildings for a variety of conditions. For many (and perhaps most) situations of fire spread between buildings, criteria of fire spread can be calculated from this model with fair reliability.

The IITRI fire-damage model consists of separate models for ignition, fire history, and fire spread. The output of each of these models (probability of ignition, flame areas, and number of burnt buildings, respectively) is computed from values assigned to the following parameters:
A. Ignition-Model Parameters: (1) Weapon yield, (2) Height of burst, (3) Location of burst, (4) Fireball radius, (5) Atmospheric attenuation (visibility), (6) Dimensions and number of ignition areas, (7) Position of a reference plane, (8) Dimensions and number of rooms, (9) Dimensions and number of windows,* (10) Building separation,** (11) Dimensions and number of buildings.** B. Fire-History Parameters: (1) Type of construction (penetration times), (2) Occupancy (fire load), (3) Wind velocity,** (4) Dimensions and number of windows. C. Fire-Spread-Model Parameters: (1) Ignition criteria for fire spread, (2) Wind velocity, (3) Building separation, and (4) Dimensions and number of buildings.

The IITRI model is not applicable for situations of very close spacing of buildings or moderate spacing with high winds, when convective heat transfer rivals radiation heat transfer as the propagating mechanism; or for situations involving very large distances between buildings where radiation is unimportant and firebrands are the only plausible means of fire spread. Concern over the criteria for fire spread for the first of these situations is probably academic, since fire spread is virtually certain, although the question of rate of spread is still quite relevant. For the second type of situation, neither rate nor probability of spread can be evaluated at present. Our knowledge of propagation by firebrands, as we have mentioned several times before, is woefully inadequate.

F.3.4 Techniques of Estimating Fire Spread in the Open

F.3.4.1 Fire Spread Through Continuous Fuels. Techniques for estimating the behavior of fire spreading through continuous fuel arrays in the open (mainly, wildland fuels) which influence urban fire vulnerability are based largely on experience with actual fires and make use of (1) criteria

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* Synergistically affects fire-history model.
** Synergistically affects fire-spread model.

for determining whether a fire will spread or not ("spread, no-spread" criteria), (2) observed fire-spread rates and their dependence on fuel and external conditions, and (3) burning duration of a variety of kinds and sizes of fuels. Chandler, Storey, and Tangren[23] have summarized the state of the art as of 1963.

Among the fire-danger rating systems commonly used in the United States and Canada, ten have as their lowest fire-danger rating, the weather conditions for various fuel types that will just constitute a threat of fire spread requiring fire-control action. Chandler, Storey, and Tangren[23] reviewed these conditions and noticed a remarkable degree of consistency among them. Accordingly, they devised a list of "no spread" criteria for the following types:

All fuels: Over 1 inch of snow on the ground at the nearest weather stations.

Grass: Relative humidity above 80%.

Brush or Hardwoods: 0.1 inch of precipitation or more within the past 7 days and:

Wind 0-3 mph; relative humidity 60% or higher, or
Wind 4-10 mph; relative humidity 75% or higher, or
Wind 11-25 mph; relative humidity 85% or higher.

Conifer Timber:

(a) 1 day or less since at least 0.25 inch of precipitation and:

Wind 0-3 mph; relative humidity 50% or higher, or
Wind 4-10 mph; relative humidity 75% or higher, or
Wind 11-25 mph; relative humidity 85% or higher.

Or (b) 2 to 3 days since at least 0.25 inch of precipitation and:

Wind 0-3 mph; relative humidity 60% or higher, or
Wind 4-10 mph; relative humidity 80% or higher, or
Wind 11-25 mph; relative humidity 90% or higher.

Or (c) 4 to 5 days since at least 0.25 inch of precipitation and:

Wind 0-3 mph; relative humidity 80% or higher.

Or (d) 6 to 7 days since at least 0.25 inch of precipitation and:

Wind 0-3 mph; relative humidity 90% or higher.

These cirteria were tested against the records of 4,378 wildland fires. Of the fires for which "no spread" would be predicted, 97.8% did not spread, but only 40% of the fires that were predicted to spread actually did spread (at a rate of 0.005 mph or faster). The authors concluded, however, that their criteria are probably not too stringent when weather conditions are known at the location and time of the fire or when the initial fire is of substantial size.

They also devised the following list of "fire-out" criteria for wildland fires based on opinions of experienced fire personnel:

Grass: "no-spread" conditions, or measurable precipitation at the three nearest weather stations.

Brush or Hardwoods: 0.1 inch of precipitation or more at the three nearest weather stations, or "no-spread" conditions for three consecutive 12-hr periods.

Conifer Timber: (a) 0.5 inch of precipitation or more at the three nearest weather stations;

Or (b) 0.25 to 0.5 inch of precipitation at the three nearest weather stations and "no-spread" conditions for the following two 12-hr periods.

Or (c) "no-spread" conditions for eight consecutive 12-hr periods and measurable precipitation at the three nearest weather stations during any two 12-hr periods.

Or (d) "no-spread" conditions for 14 consecutive 12-hr periods.

There are no data available for testing these criteria.

Chandler, Storey, and Tangren[23] also determined rates of spread of large wildland fires by examing the available information on the history of forest fires of 300 acres or more, where suitable conditions existed and were adequately known. Of the 1,261 records examined, only 697 met their requirements. From these, they obtained 1,614 linear spread rates from 333 burning periods on 110 fires. These data, none of which derive from either the fastest or slowest spreading fires on record,

were felt to be representative of rates of spread in large forest fires under any but the most extreme burning conditions. The reported rates of spread rarely exceed 1 mph; in fact, there were only three fires that had linear rates of spread greater than 1 mph, and only one fire spread rate at an average of about 1 mph for as long as 12 hr. Of the other two fires, one spread at an average rate of nearly 1½ mph for 6 hr; the other, at slightly over 1 mph for 8 hr. All of these burned in combined brush and timber on flat or nearly flat land, and moved in the general direction of a wind having velocities from 13 to 23 mph. Surprisingly, these wind velocities were not the highest found, and the burning conditions, based on the Wildland Fire Danger Rating System,[23] were not the most extreme.

The tabulated data for rates of spread show a dependence on the period of time over which the rate of spread was calculated. There were no rates of spread greater than a mile per hour for periods longer than 12-hr, and an insignificant few averaged over 1/2 mph. For 6-hr to 11-hr periods, the most frequently noted rates of spread lay between 0.1 and 0.5 mph; for 12- to 23-hr periods, 0.01 to 0.1 mph; and for 24-hr periods, the most frequently noted rate of spread was between 0.01 and 0.1 mph, although more than a quarter of the cases spread at rates less than 0.01 mph. There were a few cases of rates of spread averaging between 0.2 and 0.3 mph over 24-hr periods. It is noteworthy that almost all of the most rapid rates of spread occurred for conditions of flat or nearly flat topography.

To determine burning durations of natural fuel concentrations, Chandler, Storey, and Tangren[23] examined temperature and radiation-intensity records of experimental test fires. They noticed a consistency among the data despite the broad range of fire sizes (36 sq. ft. to 16,500 sq. ft.) and weather conditions. Their plots of temperature (or radiation-intensity) against time resembled a "log normal" distribution. They broke these curves into two time intervals:

a. Violent burning time (active flaming): period when the temperature (or radiation)* exceeds 50% of the maximum.

b. Residual burning time (mostly glowing, some flaming): period after peak when the temperature (or radiation)* is less than 50% but still greater than 10% of maximum.

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* This seems to involve an erroneous equivalence, for while radiation intensity will likely peak at the same time temperature does, by the time temperature has fallen to half its peak value, radiation intensity will have fallen off by at least an order of magnitude.

They also attempted to specify the total burning time; that is, the period over which a fire might be capable of spreading if burning conditions became favorable. These results are summarized in Table F.2, along with some estimates of fractional energy release.

The spread of fire through a forest has been modeled by Emmons[24] by assuming that the energy flux produced by the fire in the horizontal direction into unburned fuel, will be absorbed by the fuel and raise it to its ignition temperature, T_i. Radiation is assumed to be the major heat transfer mechanism in a forest fire. His coordinate system is shown in Fig. F.1. At a given time, burning fuel is located to the right of the origin, and the as-yet unburned fuel to the left. The total horizontal component of the energy flux, at x, moving toward the unburned fuel is called Q(x).

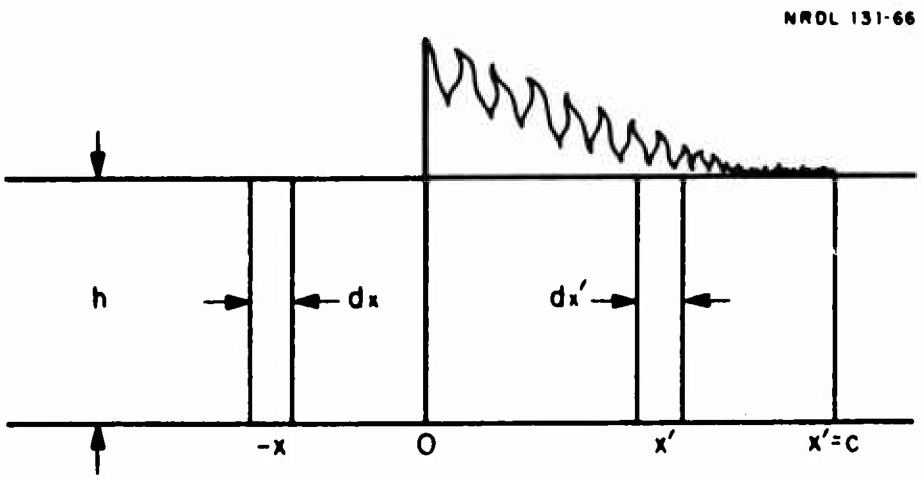


Fig. F.1 Emmons[24] Schematic For Fire Spread

TABLE F.2

Burning Durations by Fuel Type[23]

Fuel Type	Violent Burning Time (min)	Violent Burning Energy Release (%)	Residual Burning Time (min)	Residual Burning Energy Release (%)	Total Burning Time
Grass	1½	90	1/2	10	30 min
Light brush (12 tons/ acre)	2	60	6	40	16 hr
Medium brush (25 tons/ acre)	6	50	24	50	36 hr
Heavy brush (40 tons/ acre)	10	40	70	60	72 hr
Timber	24	17	157	83	7 days

$Q(x)$ is assumed to be absorbed in some fraction α per unit length. The element dx at position -x absorbs energy at the rate

$$dE_{absorbed} = - \alpha \, Q dx \tag{F.5}$$

The fraction α depends upon the fuel surface exposed at -x. If dx were a black surface, α would be equal to the entire surface per unit volume. For a forest, α is less than this due to radiation loss to the sky, the emissivity of non-black bodies, and the angular direction of the radiation input. The burning area is made up of surfaces of temperature T_b and emitting at emissivity ϵ. Hence, according to Stefan's Law, the rate of emission per unit area is equal to $\epsilon \sigma T_b^4$ where ϵ, the emissivity is a number between zero and one (closer to one for rough surfaces), σ is a constant equal to 5.6699×10^{-5} (c.g.s. units), and T_b is the Kelvin temperature of the burning surface through 2π steradians. The factors for decreasing the amount of emitted radiation which moves toward the unburned fuel are assumed to be the same as for the absorption of radiation of the unburned fuel; hence the same factor α will be used. Hence, the rate of energy production by element dx' at location x' in the burning zone is:

$$dE_p = \alpha \, \epsilon \, \sigma \, T_b^4 \, h \, dx' \tag{F.6}$$

where h = height of fuel bed and $\epsilon \sigma \, T_b^4$ is the rate of emission of a unit burning area,

or

$$dE_p = \alpha \, Q_b \, dx' \tag{F.7}$$

where Q_b = energy rate from dx' per unit width of burning front.

At -x the energy entering the element is attenuated from that passing through the point x = 0 by absorption in intermediate elements and is expected to fall off exponentially; i.e.,

$$Q(-x) = Q_o \, e^{\alpha x} \tag{F.8}$$

where Q_o is the energy flux at the origin. Similarly, by observing that some of the energy emitted by each element is absorbed by fuel lying between it and the origin) Q_o is given by:

$$Q_o = \int_0^c e^{-\alpha x'} dE_p = \int_0^c e^{-\alpha x'} Q_b \, dx'$$

$$= Q_b \, (1 - e^{-\alpha c}) \tag{F.9}$$

Substituting into Eq. F.8,

$$Q(-x) = Q_o\, e^{\alpha x} = Q_b\, e^{\alpha x}(1-e^{-\alpha c}) \qquad (F.10)$$

In order for the fire to propagate steadily $\left(\text{velocity, } u = \frac{x}{t}, \text{ or } \frac{dx}{dt}\right)$ the energy accumulated by an element as the fire front moves from $-\infty$ to 0, must equal the heat required to raise its temperature from ambient (T_o) to the ignition temperature (T_i). In other words, the heat per unit time supplied to the fuel must be proportional to the rate of fire spread in the bed, viz.

$$Q_o = M\, C_p\, (T_i - T_o)\, u = Q_b\, (1 - e^{-\alpha c}) \qquad (F.11)$$

where M = mass of fuel per unit area of forest floor and

C_p = the specific heat of the fuels.

The characteristic time taken to burn a given amount of the bed can be expressed either as $\tau = \frac{M}{w}$ where w = mass burning rate (per unit horizontal area of bed)

or $\tau = \frac{c}{u}$ (the time taken for the front to move a distance equal to the width of the burning zone)

therefore, letting $\frac{c}{u} = \frac{M}{w}$

or

$$c = \frac{Mu}{w} \qquad (F.12)$$

Substituting (F.12) into (F.11):

$$M\, C_p(T_i - T_o)u = Q_b\, (1-e^{\frac{-\alpha Mu}{w}}) \qquad (F.13)$$

Arranging (F.13) into dimensionless terms:

$$\underbrace{\left(\frac{w\ C_p(T_i - T_o)}{\alpha\ Q_b}\right)}_{P}\underbrace{\left(\frac{\alpha M u}{w}\right)}_{U} = \left(1-e^{\frac{-\alpha M u}{w}}\right)$$

Where P is the burning characteristic, and

U is the fire-front velocity

or $$PU = 1 - e^{-U} \qquad (F.14)$$

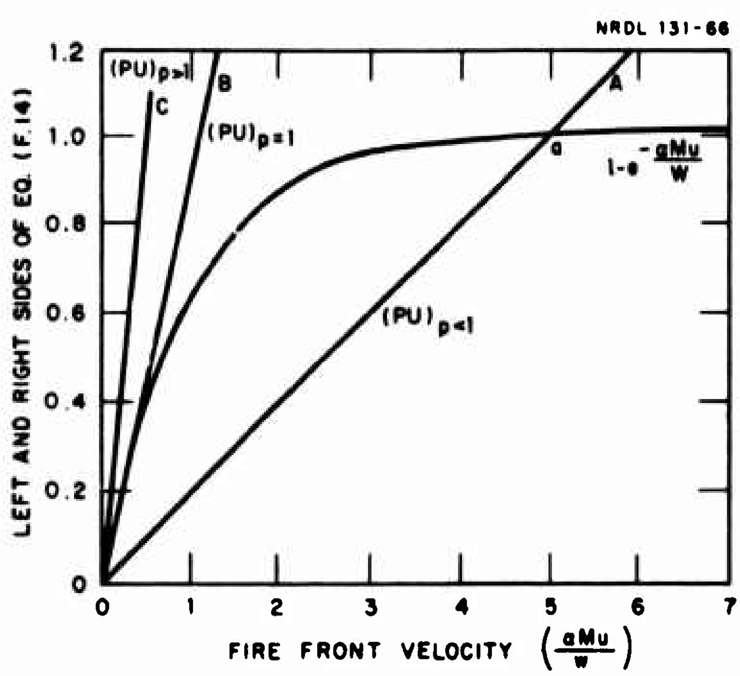


Fig. F.2 Graphical Solution of Eq. (F.14)[24]

From the graphical solution of Eq. (F.14) shown in Fig. F.2 it can be seen there is only one real solution, at a, and this occurs for burning characteristic $P<1$ (see also Fig. F.3).

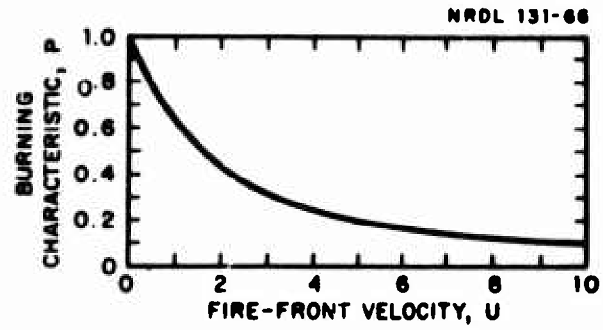


Fig. F.3 Fire-Front Velocity, U Vs Burning Characteristic, P [24]

P, the burning characteristic can be interpreted as the ratio of the (1) energy required to heat the fuel in an elemental thickness up to the ignition temperature to (2) that fraction of the energy given up by the same elemental thickness as it burns (completely) propagating toward the unburned fuel. U is proportional to the velocity and also to the width of the burning zone.

In addition to the above model treating continuous fuels, Emmons[24] has (1) shown that the function PU is virtually the same function as $B(\frac{g}{h})$ where B is the fraction of energy getting across a firebreak of span g in a fuel bed of height h, and has (2) mathematically modeled fire buildup. Ref. 24 should be consulted for further details.

F.3.4.2 Fire Spread from Building to Building: In general, less information is available on "spread, no-spread" conditions, rates of fire spread, and burning times for urban fuels (in the form of buildings and their contents) than for wildland fuel. The following quote is from Chandler et al.,[23] "Records of local fire departments usually show the time fire started, when controlled, and the number of buildings involved, but they include no maps or other indication of the location of the fire front at specified time intervals. Urban fire reports stress cause, equipment used, and monetary damage. Very few fire departments keep their reports on punch cards, and it is therefore time consuming to summarize number of fires and fire characteristics for special studies."

"The fire Record Department of the National Fire Protection Association (NFPA) has a special 1-page Fire Report which it sends to the local fire chief whenever it hears that the city has had a large or unusual fire. Usually these are spreading fires. Space is provided on the form for sketching a fire map and recording weather conditions. Short case histories of most larger fires are published in the NFPA Quarterly, often with fire maps. However, only rarely do these accounts contain enough information on time and distances to compute rate of spread. They describe fuels in great detail, but usually do not include weather data. After very large conflagrations or very damaging smaller fires, either the NFPA or the National Board of Fire Underwriters, or sometimes both, will send a special team of investigators to study [the fire] and prepare a detailed report on the fire. These reports are the best source of time-and-distance data for computing rates of spread. Many excellent reports that contain enough information to compute rate of spread have been written by laymen and are available in libraries."

"Although the United States Strategic Bombing Survey reports contain no information on rate of spread, their fire maps showing final area of burnout include data that can be useful for checking model output."

"In recent years, many of the largest urban conflagrations in the Western Hemisphere have occurred in Canada. Unfortunately, very few published reports are available on these fires."

"Urban conflagrations continue to occur in the United States. Many of these could furnish valuable information on rate of spread if an effort were made to obtain these data. Urban fire reports could be extended or revised to require noting or mapping the fire perimeter or at least the position of the [head] front at specified times. The NFPA's Fire Report could be revised to make more specific requirements for times and distances for fire spread. Weather data during the fire usually is readily available at the local Weather Bureau Office--unless the office burns up as in the Great Chicago Fire and the San Francisco

Earthquake Fire."

To provide criteria for estimating whether fires would spread in urban areas and if failing to spread, when they would burn themselves out or be extinguished by precipitation, Chandler et al.[23] relied heavily on a few large urban fires in Canada and the United States, accounts of fires following incendiary raids of World War II, and opinions of experienced fire chiefs.

Large urban American fires provide 14 examples of fires that were stopped primarily by factors other than direct fire fighting. The most important factor was fuel depletion (low built-upness or large fuel gaps), but changes in weather, particularly in wind speed and direction, were factors in some cases. Precipitation and increased humidity probably do not contribute much to the limitation of spread, since building fires are protected by the enclosure during fire development, and the bulk of the fuel on which they feed is conditioned by the environment within the enclosure.

Chandler et al.[23] proposed the probability-of-spread curves of Fig. F.4 (based on similar curves developed by Sanborn[25] from data on an incendiary-raid fire in Hachioji, Japan) as a basis for "no-spread" criteria in urban areas. They point out that some experts expect a great deal of fire-behavior similarity between Japanese and American cities. These curves give some indication of the effect of the two most important parameters: fuel loading (built-upness) and wind. They do not, however, allow for the effect of different wind speeds or different features of construction (building dimensions, exterior features, window areas, etc.).

They further proposed the following "fire-out" criteria for four classes of urban land-use areas:

Light residential: 1.0 inch of precipitation before the fire at the Weather Bureau Station and "no-spread" conditions for 36 consecutive hrs, or "no-spread conditions for 48 consecutive hrs.

Heavy residential: 1.5 inches of precipitation before the fire at the city Weather Bureau Station and "no-spread" conditions for 72 consecutive hrs, or "no-spread" conditions for 100 consecutive hrs.

Commercial: 2.0 inches of precipitation at the city Weather Bureau Station before the fire and "no-spread" conditions for 7 consecutive days, or "no-spread" conditions for 10 consecutive days.

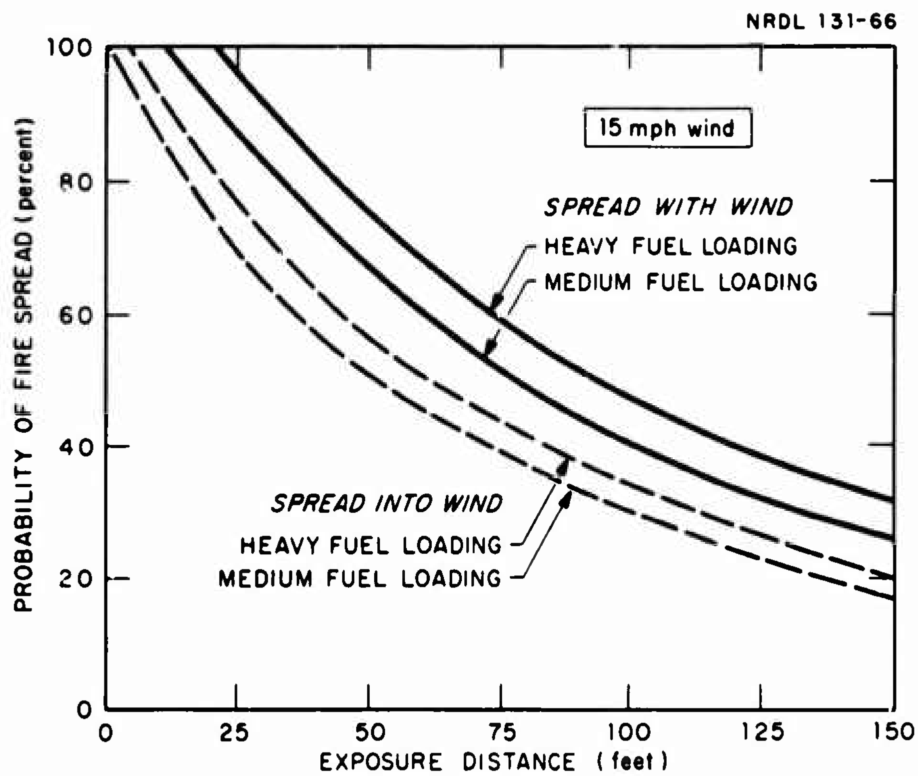


Fig. F.4 Probability of Urban Fire Spread According to Chandler [23]

City Center or Massive Manufacturing: 2.0 inches of precipitation at the city Weather Bureau Station before the fire and "no-spread" conditions for 2 consecutive months, or "no-spread" conditions for 3 consecutive months.

Intuitively, we expect the building density to be an important factor in fire spread. Numerous analysts have considered fire-spread experience in terms of built-onness (ratio of roof area to total area) in searching for correlation.[25,26,27,28,29] It has been noted that the majority of cities that suffered mass fires during World War II had building densities (built-onness) of 30% or greater. Reference 26 estimates that cities 0 to 5% built-on have no significant risk of fire spread from isolated fires, cities 6 to 20% built-on are likely to exhibit local spreading but no mass-fire phenomena, and cities built-on more than 20% constitute a significant firestorm or conflagration risk.

Rogers and Miller[29] present a series of curves (shown here as Figs. F.5 to F.7) which are derived from material first published in one of Horatio Bond's books.[25] From the same source of data, Carl Miller[28] derived a relatively simple expression relating the fraction of urban areas burned* to the built-onness: viz,

$$b_e = 1.88\,B^{1.2} \qquad \text{(F.15)}$$

where b_e is the fraction of exposed areas burned, and B is the fractional building density. Eq. (F.15) suggests (on extrapolating to $b_e = 1$) that an urban area must be 59% built-on for fire-destruction to be complete. But the firestorm area of Hamburg, an area of virtually complete fire destruction, was only 30% built-on. This might be interpreted as indicative of the greatly enhanced destructiveness (at least locally) of firestorms over more conventional large-scale fires.

The Directorate of Intelligence of the U.S. Air Force comprehensively analyzed preattack and postattack aerial photographs of certain European and Japanese cities that suffered incendiary- or atomic-bomb attacks during World War II with the objective of evaluating the principal parameters affecting the spread of fire in urban areas so that the vulnerability of such areas to fires resulting from bombings could be estimated. The report surmises that wind, temperature, rain, humidity, terrain, building construction and contents, building areas and heights, building density, building contiguity, and firefighting activity are the principal fire-spread variables. The investigators found it infeasible, however, to assess most of these parameters. They, therefore, concentrated on those factors that could be readily assessed from photography.

* When exposed to a spreading fire, presumably.

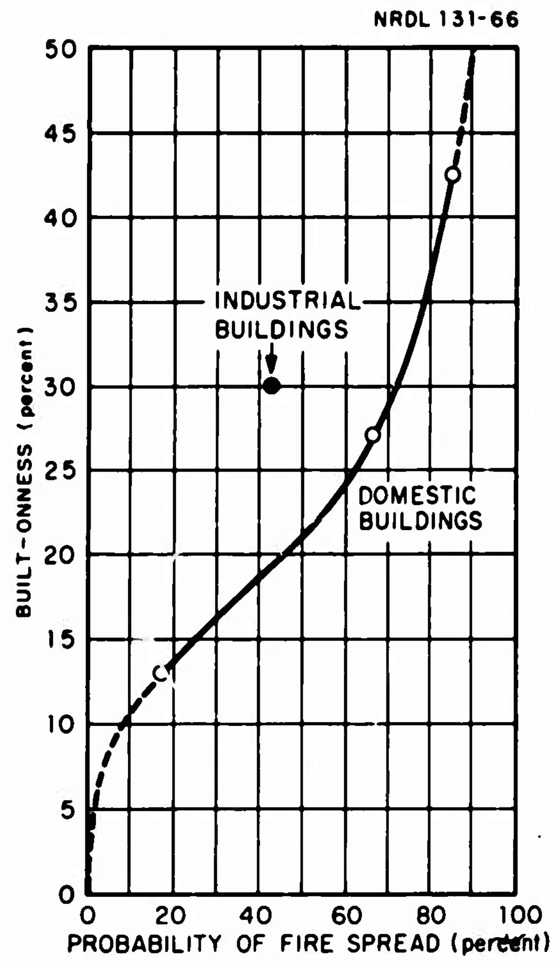


Fig. F.5 Probability of Fire Spread in Various Amounts of Built-Onness[29]

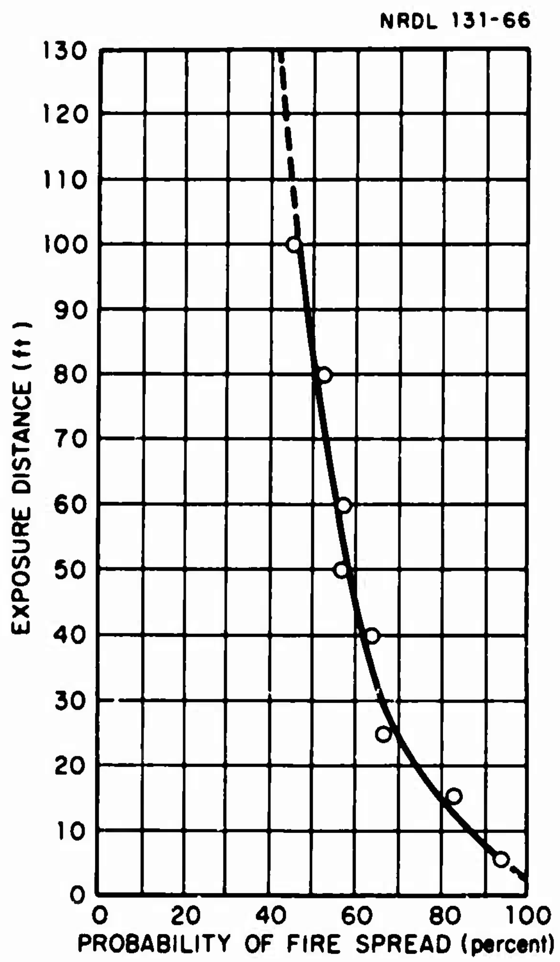


Fig. F.6 Probability of Fire Spread Across Various Exposure Distances[29]

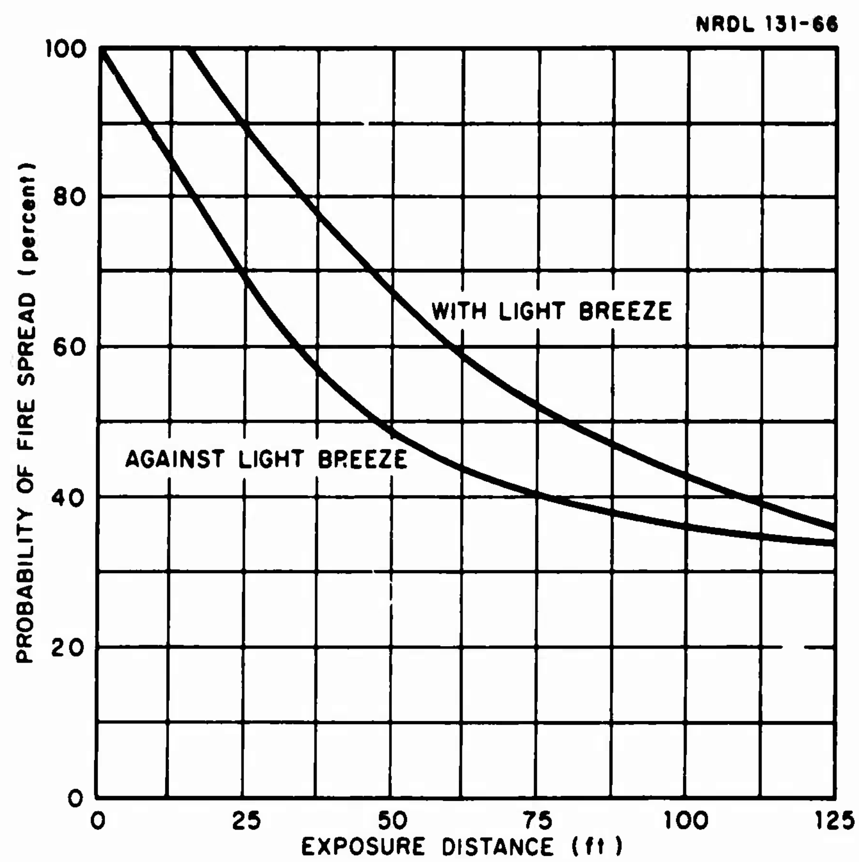


Fig. F.7 Relationship Between Fire Spread, With and Against a Light Breeze, and the Probability of Fire Spread Across Open Spaces[29]

Deciduous trees in leaf were found to have some retarding effect on the spread of fire, presumably by shielding the nearby buildings from radiation. They determined that building construction and contents strongly affected the spread of fire. They failed, however, to establish a consistent correlation among building density, building volume or building height, and the distances that stopped the spread of fire. Consequently, they were forced to develop separate consolidated curves for the German cities and for the Japanese cities, for cumulative points of observation vs corresponding burned-to-unburned distances without regard to details of building density and construction. These curves, though they are valid for making estimates of the extent of fire spread in cities of very similar construction to the cities from which the data are derived, have served as a basis for a large number of fire-jump-probability curves of doubtful validity for general use.

Still another (slightly different) approach to the building-to-building fire-spread problem is advanced by Byrne[30] based on the radiation fire-initiation work of Margaret Law[31] and Bevan and Webster.[32] Radiation configuration factors are given for a variety of building sizes and separations. These are summarized in Table F.3 for a particular ratio of window area to total surface area (25%). Configuration factors for other window openings are proportional to this ratio. Similar more extensive tables are published in The Builder in an article by Langdon Thomas.[33]

Byrne constructs a curve of probability of spread vs configuration factor (without giving much detail of how it was done) and provides some rules for accounting for wind. From these relationships, the curves such as Fig. F.8 may be derived and may be compared with related curves of Willoughby and Phung[34] (Fig. F.9) and Chandler[23] (Fig. F.4). Crombie and Pritchard[36] use data such as that presented by Byrne in their calculations of the probability of fire occurring in uncrushed dwellings exposed to the thermal radiation of a nuclear explosion. At first glance the various probability-of-spread curves generally appear to be similar. However, it should be noted that there are rather large differences. Also the curves of Byrne are based strictly on radiation spread, whereas Chandler et al. and Willoughby and Phung's curves are based on real measured fire-spread data (limited to be sure) that would include processes other than radiation in its mode of spread.

F.3.5 Fire Spread Models

F.3.5.1 Basic Parameters and Approaches: Phung and Willoughby[37,38] have recently presented several mathematical fire-spread models that are semi-empirical in approach and make use of both stochastically and deterministically described parameters. They point out that such models

TABLE F.3

Configuration Factors[30]

Width of Separation, e.g., of Street (FT)	Height of Bldg on Fire (FT)	Length of Building on Fire (FT): 25	50	100	200	∞
		Configuration Factor on Exposed Elevation for a 25% Window Opening				
		Φ	Φ	Φ	Φ	Φ
20	25	0.082	0.180†	0.128**	0.130***	0.130**
	50	0.115**	0.166†	0.189†	0.197*†	0.197†
	100	0.125**	0.189†	0.221†	0.232*†	0.232†
40	25	0.026	0.033	0.046	0.075	0.076
	50	0.047	0.082	0.114**	0.125**	0.130**
	100	0.065	0.114**	0.166†	0.189†	0.197†
	150	0.070	0.124**	0.182†	0.212**†	0.221**†
60	25	0.012	0.024	0.040	0.049	0.055
	50	0.024	0.044	0.071	0.089	0.097**
	100	0.040	0.071	0.115**	0.148†	0.158†
80	25	0.008	0.014	0.025	0.034	0.040
	50	0.014	0.026	0.048	0.065	0.076
	100	0.025	0.048	0.082	0.114**	0.130**
	150	0.033	0.059	0.101**	0.114**	0.168†

* At this separation, the 200-ft-long building is virtually infinite.
** Indicates > 50% probability of spread as determined from Ref. 30, Fig. A7.
† Indicates > 90% probability of spread as determined from Ref. 30, Fig. A7.

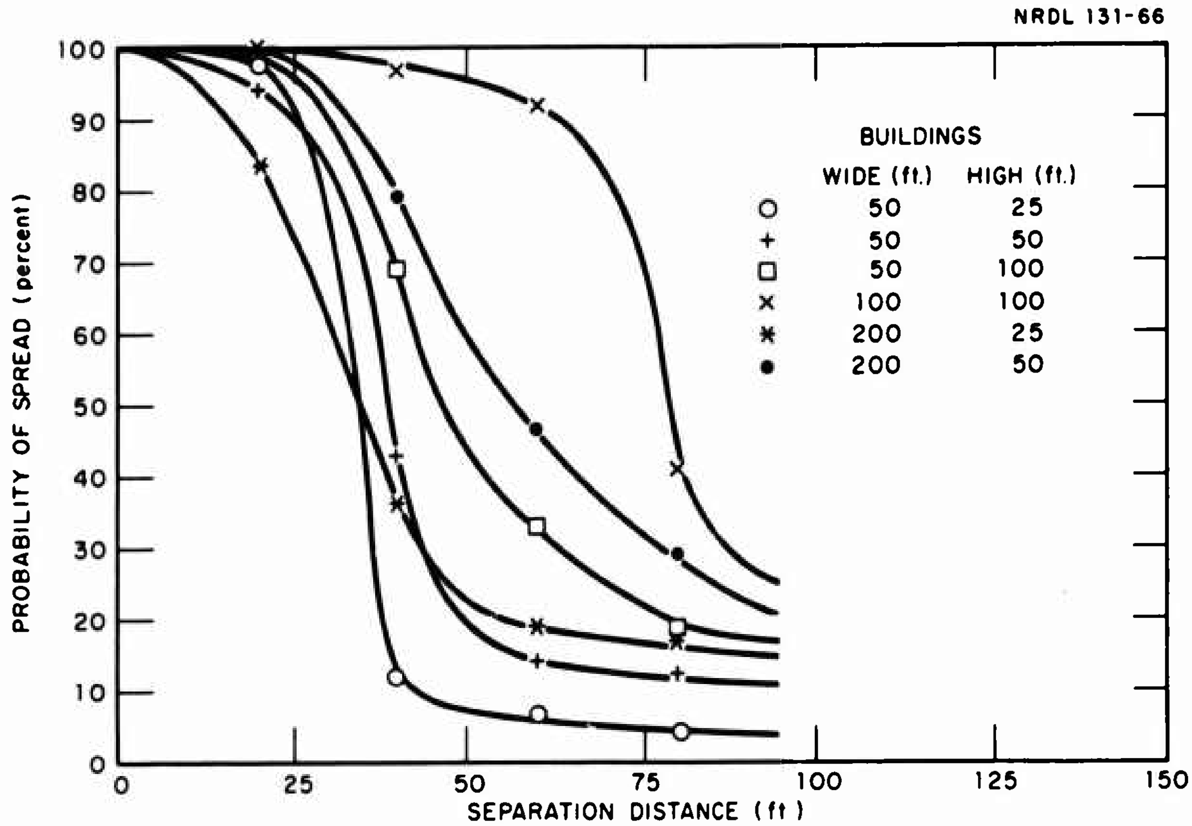
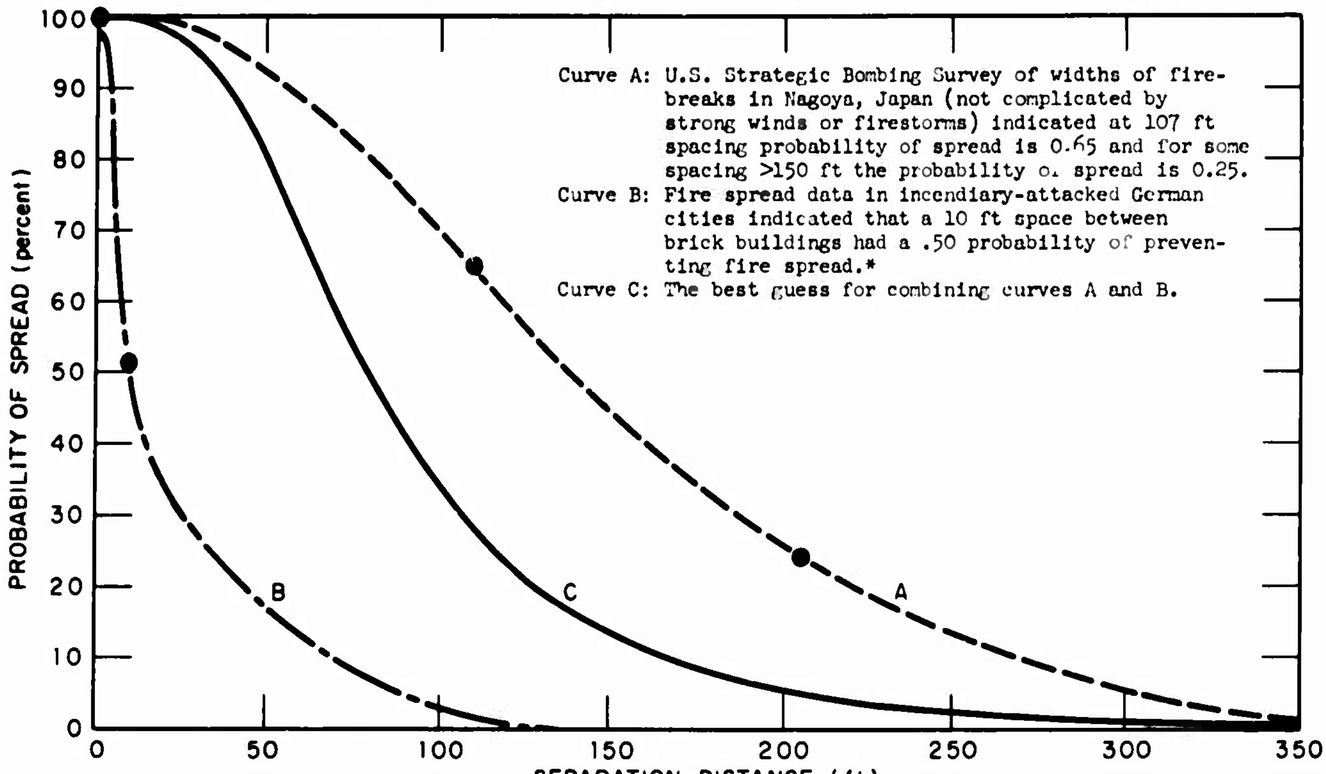


Fig. F.8 Probability of Fire Spread Vs Separation Distance Based on the Configuration Factors and Probability of Byrne[30]



* Ref. 35

Fig. F.9 Probability of Spread Vs Separation Distance According to Willoughby and Phung[34,38]

may be applied in pre-attack planning and post-attack damage assessment, and that in either application, the amount of detail in both input and output information is determined by the geographical scale of the analysis--national, regional, or local.

They classify fire-spread parameters as fuel, weather, and topography. Fuel parameters include type, concentration, spatial distribution, age, fineness, and moisture content. Weather parameters include wind speed and direction, humidity, precipitation, and temperature. Topographical factors include slope, altitude, and relief. They discuss the relative importance of these parameters and point out that some affect the extent of spread more than the rate of spread, whereas others mainly affect rate, intensity, and burning time.

In introducing the subject of models, they suggest that the purely theoretical approach (though it might be the most desirable if we knew the physics well enough) and the purely empirical approach are, at the present state of the art, less appropriate than semi-empirical approaches, which make optimal use of experimental data and propagation theory. Details of a model based on the latter approach are determined largely by the stochastic or deterministic character of the parameters. It is impractical, or frequently impossible, to treat some variables in a deterministic way. On the other hand, a heavy reliance on stochastic parameters causes the mathematical procedures of the model to become excessively complicated and the results to be more unreliable and more difficult to interpret than those for a more deterministic model. It is important, they point out, to decide which parameters can be treated deterministically and to use stochastic parameters where unavoidable. Fuel parameters can be treated deterministically (with a great deal of work) if the area of analysis is not very large, that is, less than 30 square miles. If only average values of fuel parameters are available, for reasonably homogeneous areas they must be applied in an appropriate stochastic model. Some parameters, such as weather, can be treated deterministically.

F.3.5.2 <u>Two Examples of Basic Kinds of Model</u>: Phung and Willoughby[37] discuss two basically different kinds of model with a variety of modifications for various purposes. The first kind, called a "fire-front model," uses the concept of a random walker progressing through an array of cells. The fire-propagation property of the cells is expressed in terms of a "spread parameter" and a "decay parameter,"* which in turn are complicated functions of fuel, weather, and topographical parameters.

* The "decay parameter" is the reciprocal of the mean lifetime of the fire, is independent of time, and is determined by fuel characteristics in a more or less extended region and possibly by weather conditions.

Using this model (or a modification of it that accounts for spotting), one can calculate the position of the front as a function of time, the burn-out distance, and the lifetime of the fire. The spread parameter is capable of empirical evaluation, but the decay parameter cannot be determined with currently available information.

The second kind of model is called a "fuel-state model" and is based on the mathematics of epidemic spread of a disease. Fire conditions, such as the flaming state, the unignited state, and the burned-out state, are substituted for epidemic phenomena, such as susceptibility, incubation, infection, and removal of victims by isolation or death. In the stochastic version, spread and decay parameters similar to those of the fire-front model are introduced. For the solutions worked out in the report,[37] these two sets of parameters bear a striking resemblance to one another. They also suffer the same weaknesses: they cannot be evaluated with existing data (particularly, the decay parameter). The spread parameter can be gotten from data on rates of spread (a fair amount exists for wildland fuels; a much lesser amount for urban fuels). The decay parameter could be evaluated from fuel burning times, but reliable information is unavailable.

Phung and Willoughby[37] give two deterministic versions of the fuel-state model. One relates the rate of spread to the heat flux on the unburned fuel from the burning fuel. For the set of assumptions used, three parameters are derived. These parameters can be related to the spread and decay parameters of the previous stochastic kind of models. Again, there is insufficient data to permit evaluation. One important result of this version and the stochastic version of the fuel-state model is that, except for a narrow range of conditions (ratio of spread to decay parameters less than 1, but not much less), fires will spread either a negligible distance or indefinitely. Thus, to a fair approximation, spread conditions can be divided into a spread group and a no-spread group.

The foregoing point is a basic tenet of the other (and final) deterministic version of the fuel-state model--a two-dimensional model that can be used (the only one of these versions that can be) at the present state of fire-spread knowledge. In this model, the area of interest is divided into cells of equal size, and at any time, each cell is assigned one of five states: susceptible, immune, ignited, burning, or burned out. The difference between the ignited state and the burning state is the time required for the fire to propagate across the cell (incubation time in epidemic terminology), which can be evaluated from rate-of-spread data. The following information is required to implement this model:

1. The type of fuel in each cell.

2. A spread vs no-spread table giving the range of weather conditions for each type of wildland (rural) fuel and the fuel conditions for each type of urban fuel under which the fuel is either susceptible (fire will spread through the fuel indefinitely), or immune (fire will not spread through the fuel).

3. A rate-of-spread table, giving the rate of fire spread for each fuel type as a function of the pertinent weather and topographic parameters.

4. A burning-time table, giving the burning time for each fuel type as a function of pertinent weather parameters.

5. For adjacent rural fuels, weather conditions for seven days prior to the assumed starting time and a forecast of future weather conditions (historical data may be used if adequately forecasted information is not available).

6. The initial burning conditions (the cells that are initially ignited, burning, or burned out).

The first step in applying the fuel-state model is to establish the initial state of each cell, which can be accomplished from the fuel and weather data, the spread vs no-spread table, and the specified initial burning conditions. The state of each cell is then redetermined at the end of each successive small time increment Δt until a weather change occurs, using the following rules:

a. A cell in the immune state will remain in that state.

b. A cell in the susceptible state will instantly change to the ignited state if the cell is immediately adjacent to a cell in the burning state.

c. A cell in the ignited state will change to the burning state when the time after ignition is equal to or greater than the "incubation time."

d. A cell in the burning state will change to the burned-out state when the time after start of the burning state is equal to or greater than the burning time of the fuel.

e. A cell in the burned-out state will remain in the burned-out state.

In choosing a fire-spread model from the foregoing variety of models, Phung and Willoughby[37] recommend using deterministic versions for rural

areas (particularly where the area is not exceedingly large) and stochastic versions for urban areas. To simplify computation, they recommend using linear models wherever possible except in the case of the last model discussed in which two-dimensionality presents no serious difficulties.

Phung and Willoughby also analyzed statistically the data of Chandler et al.[23] They rejected rate-of-spread data for rural (wildland) fuel fires taken over periods of time less than 9 hr (includes most of the cases of very high rates of spread) and all cases of spread rates greater than 0.1 mile/hr because they suspected a bias in observation. They found no significant effect of topography and little effect of fuel type on rate of spread of rural fires. They estimated the rate of spread in still air (30% to 45% relative humidity) to be about 0.02 mph, with about 0.02 mph increase in rate in the direction of the wind with each 10 mph of wind speed. In the report,[37] they summarize the rural fire-spread data by tabulating rate of spread for a series of wind speed ranges (0-5, 5-10, 15-20, 20-25, and 25-30 mph), ranges of angles between direction of fire propagation and wind direction (0-45°, 45-135°, and 135-180°), and relative humidity ranges (0-15, 15-30, 30-45, and 45-60%).

In reviewing the urban fire-spread data, they classed structures as follows:

1. Light wooden
2. Heavy wooden
3. Light stone or concrete
4. Heavy stone or concrete.

But at a later stage in the analysis, they grouped the very limited data for Class 4 with those of Class 3. They also classified the building-density values for the reported urban fires into four categories:

I. $< 20\%$

II. 20% to 29%

III. 30% to 39%

IV. $\geq 40\%$

They found that the average ground spread rate decreased from 0.26 mph for Class I-1 to 0.03 mph for IV-3, and that the spread rate for IV-3 (the most populous data class) obeyed the equation:

$$R = 0.027 + 1.25 \times 10^{-3} W \qquad (F.16)$$

where R is the rate of spread and W is wind speed, both in miles per hour.

Fire-spread by spotting was observed with much higher frequency for fuel-class 1 (I-1 and II-1) but there were considerably more observations of ground spread than spotting for fuel classes 2 and 3 (III-2, II-3, and IV-3). This difference does not necessarily mean, however, that spotting is a more important factor in light than heavy construction, though it may be.

Rate of spread by spotting decreased from 0.33 mph for Class I-1 to -.06 mph for Class IV-3. There did not appear to be a strong dependence of the occurrence of spotting on wind velocity.

Fuel density was found to be the most important factor in the spread of fire in urban areas, and it was the only factor that could be quantitatively studied in the report. The combined averages (ground spread and spotting in all fuel types) for rate of spread are 0.28, 0.29, 0.07, and 0.03 mph for fuel densities of Classes I, II, III, and IV, respectively. The other parameters considered--humidity fuel class, topography, and wind direction--did not show significant influences in the admittedly poor, available data.

Thus far in the discussion of the fire-spread models of Phung and Willoughby,[38] we have primarily considered the location of the fire front (or region of fire activity) and the extent of the area that has been swept by fire with time during the fire's history. In continuous fuel arrays, this information tells the whole story, at least from a damage-assessment point of view; but in the largely discontinuous fuel distributions of urban areas, it may leave us quite ignorant of the extent of fire damage. We commonly observe buildings and other resources being left unburned in the midst of a burned out area in conventional fires; even in the so-called firestorm area of Hiroshima, there were buildings that survived the catastrophe. It is desirable, therefore, to have a means of estimating the vulnerability to destruction by fire of selected resources in an area expected to be swept by fire. For such estimating, it is necessary to specify (1) the features of the resource (for example, structural characteristics and contents of a building) that will determine its responses to fire environments, (2) the characteristics of adjacent fuels that will determine the nature of the resource's fire environment, and (3) the spacing between resource and adjacent fuel.

The Phung and Willoughby report[37] treats as resources only the case of typical urban buildings and considers three environments: urban, rural and mixed. A deterministic approach can be used when detailed

information about the environment is known: size of, configuration of, and distance to adjacent fuel concentrations. Stochastic approaches are indicated when such details are lacking.

In the urban environment, the recommended deterministic approach involves estimating whether ignition of fuels will occur in the building in question, based on the incident irradiance level (of radiation emitted by surrounding, burning structures) adjusted to account for convection and embers. This technique is comparable to that used in the IITRI fire-spread computer program (see F.3.2). For each adjacent structure, a configuration factor is estimated that, when multiplied by the expected radiation intensity at the source, provides a measure of the irradiance contribution of each adjacent structure to the exposed surface of the building (the resource) whose vulnerability is required. These contributions are then summed up in a manner that reflects the anticipated fire progress through the environment. The original reference[37] should be consulted for details.

If only the number and distances of adjacent structures are known, average construction details for the general type of urban surroundings must be assumed. The probability that the building will burn is given by:

$$P = 1 - \prod_{n} \left[1 - P(d_n) \right] \qquad \text{(F.17)}$$

where $P(d_n)$ is the probability that fire will jump a distance d_n corresponding to the separation of the n-th building and the resource. Values of $P(d_n)$ can be estimated from Fig. F.9 and other similar fire-jump-distance relations such as Fig. F.4 and Fig. F.8.

The most stochastic situation would be one in which neither structural characteristics nor spacing between buildings is specified. For this situation, both bits of information must be inferred from typical characteristics of such urban areas. This inference can probably best be done by dividing urban areas into land-use classes (see App. A) and determining for each class, either for the particular urban area in question or from a large number of different urban areas, the average building characteristics and the frequency distribution of spacings. As an example of the latter, a table could be constructed as follows (where n_i represents a general term of the type n_1, n_2, etc):

Number of Buildings in Residential Tract	With Spacings Between:
n_1	0 and 5 ft

n_2	5 and 10 ft
n_3	10 and 15 ft
n_4	15 and 20 ft
n_5	20 and 25 ft
n_i	. . . .

The probability that the resource structure would be ignited by one or more structures separated from it by a distance in the i-th range is

$$P_i = 1 - \left[1 - P_{(i)}\right]^{n_i} \qquad (F.18)$$

where $P_{(i)}$ is the average probability that fire will jump a distance in the i-th range, and is determined from a fire-jump-distance curve, such as those mentioned in the previous paragraph. Accordingly, the overall vulnerability of the resource is:

$$P = 1 - \prod_{i=1}^{\infty} \left[1 - P_{(i)}\right]^{n_i} = 1 - \prod_{i=1}^{\infty} (1 - Pi) \qquad (F.19)$$

When the resource is located in a purely rural environment or a mixed urban-rural environment, the information needed for stochastic treatments is not available. It is therefore necessary to have a detailed description of the surroundings of the resource and to use a deterministic approach, such as the adjusted radiant-heating calculation described above for urban areas. The Phung and Willoughby report should be consulted for details.

F.4 INTERACTIONS OF FREE-BURNING FIRES: COALESCENCE

F.4.1 General

There are two ways in which interaction between fires can have a bearing on the nature of the fire in an urban area. When free-burning fires are burning at great distances from one another, they act, for all practical purposes, as if they were isolated; but as they are brought closer together, their flames begin to lean toward each other. This affinity to interact has the effect of increasing the rate of spread

of each toward the other. When they get quite close, the rate of burning is increased by the concerted convective action of the interacting fires, which brings in air at a greater rate at the base.

The second way in which the effects of fire-interaction may be seen is, if there are a large number of fires burning in close proximity, the coalescing of the individual convection columns to produce a condition of high surface winds and very intense burning. This condition can be described as a mass fire or, in some cases, a firestorm.

F.4.2 Experimental Work With Coalescence of Convective Columns from Small-Scale Free-Burning Fires

F.4.2.1 Coalescence of Multiple Wood Crib Fires: Fire experts assume coalescence of the convective columns of individual fires as a prerequisite for conflagrations or firestorms, the most destructive fire phenomena. An understanding of the fundamental effects of the merging of the convective columns of multiple fires upon (1) burning rates and (2) rate of spread between the fire is important in order to explain the mechanism of the build-up of small fires into a large fire and for the prediction of the occurrence of mass-fire phenomena.

Since it is impossible to study full-scale mass fire phenomena in the laboratory and infeasible to burn entire urban areas under proper conditions, the simulation of the interaction of convective columns of fires is generally undertaken in the laboratory or in the field.

A limited amount of data is available on the coalescence of multiple small-scale wooden-crib fires. Waterman et al.[6] have shown that flame coalescence may be suitably described in terms of the burning rate for such fires. They found that the total burning rate of a group of cribs increased as the distance between individual cribs increased until the transition from coalesced fire to non-coalesced fire occurred. With this transition the burning rate suddenly decreased. At the transition distance the peak burning rate could be described by the following equation:

$$R_{peak} = 1.56\ n\ R_s \qquad \text{(F.20)}$$

where R_{peak} is the peak burning rate of the entire fuel mass, n is the number of cribs, and R_s is the burning rate of an individual crib. For a coalesced fire at the peak burning rate, the ratio of the distance between cribs to the dimension of the individual crib was found to be:

$$\left(\frac{\text{distance between cribs}}{\text{crib dimension}}\right) = 0.069(n\ R_s)^{0.4} \qquad (F.21)$$

From Equations (F.20) and (F.21) it is apparent that the burning rate of each crib fire and the total number of fires is important in determining the separation distance at which coalescence occurs and the intensity of burning at this distance. A graphical representation of the results obtained by Waterman et al.[6] is shown in Fig. F.10. The values of the maximum burning rate (as shown in Fig. F.10) must be considered as imprecise points as they do not coincide with experimental points. Another point of interest with regard to Fig. F.10 is the fact that as the separation distance between cribs is decreased from that corresponding to the maximum burning rate, the burning rate, in all cases, is less than that of cribs spaced infinitely far apart; one explanation for this being the decreased flow of oxygen to centrally located cribs.

F.4.2.2 <u>Coalescence of Multiple Gas-Burner Fires</u>: Thomas et al.[39] have considered the merging of flames issuing from two burners (surface-combustion radiant panels 30 cm square) supplied with town gas. The flame height and separation distance between burners were measured and the condition when the flames just merged was determined. Theoretically, the flame height (L) is related to the length of the long side of the fuel bed (W), separation distance (S), and dimension characteristic of the burning zone (D) according to the following equation:

$$\frac{L}{D} = 9\ (S^3/DW^2)^{\frac{1}{2}} \qquad (F.22)$$

$\frac{L}{D}$ is referred to as the dimensionless flame height, and $(S^3/DW^2)^{\frac{1}{2}}$ is the spacing factor. These results are limited to the merging of two burner flames; they will probably be extended in the future by Thomas to more complex situations. However, equation (F.22) may be used for reasonable estimates if flame heights are not very small, or if the ratio S/D is not large. Gas burners have the disadvantage of not burning evenly over their entire area at very small gas flows, in which case the separation between flames is larger than that measured between the burners.

F.4.2.3 <u>Coalescence of Multiple Liquid-Fuel Pool Fires (Small)</u>: All free-burning fires undergo three regimes dependent upon the diameter of the fuel source: a. laminar, b. transitional, and c. turbulent. Waterman et al.[6] have indicated from a study of the pertinent literature that turbulent fires occur when their diameter is greater than 30 inches. Liquid hydrocarbon (JP-4) ignited in a shallow open 30-in square pan by IITRI researchers resulted in unstable flaming even after attempts to balance air flows by placing barriers about the fire and by adding ceramic beads to the pan in order to alter the mode of preheating.

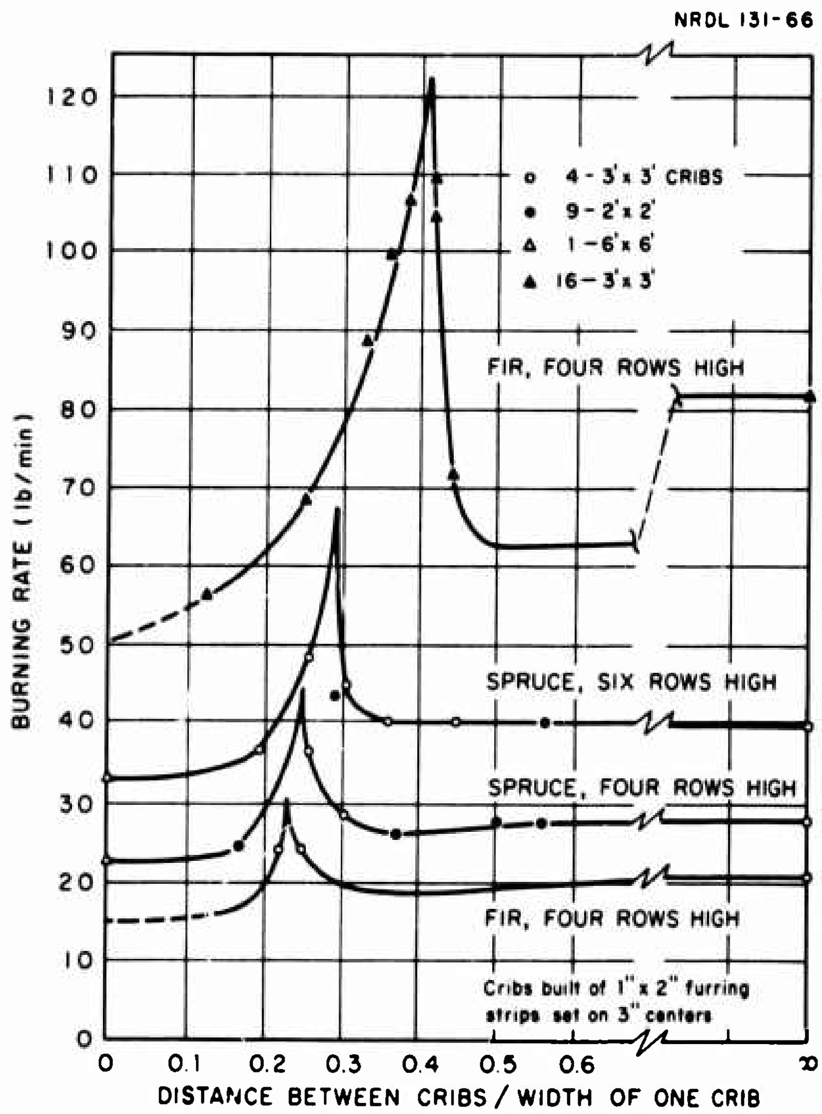


Fig. F.10 Burning Rate as a Function of the Distance Between Cribs[6]

Severe difficulties are encountered in the study of the coalescence of liquid-fuel pool fires primarily due to the unstable burning of individual pools. Fuel vapors often ignite some distance away from the pools, which in addition to local heating such as at the pool edges, result in disturbances of the flames, and coalescence of flames above the pool. Little quantitative information on the coalescence of flames has been achieved with small liquid pool fires.

F.4.3 Experimental Work With Coalescence of Convective Columns from Large-Scale Free-Burning Fires

F.4.3.1 Coalescence of Multiple Liquid-Fuel Pool Fires (Large): The IITRI has performed a number of large-scale liquid-fuel pool fires in which burning rates, flame heights, flame areas, and flame angles were photographed (burning rate was measured by the position of a lever indicating the depth of No. 2 fuel oil in the pan). It was found that the burning rate was constant during the stable portion of the fire, which indicates that natural and induced wind velocities (5-15 mph for most tests) were not large enough to have a significant effect on the burning rate even though some fires had coalesced and others had not.

The tests indicated that coalescence was obtained in the direction of the wind, but to varying degrees perpendicular to the wind. A wind velocity of 5 mph tilted the flames about 30° from the vertical, whereas a 10-15 mph wind velocity tilted the flames 45° or greater from the vertical.

F.4.3.2 Coalescence of Simulated Urban Fuel Fires: Countryman[40] has simulated urban areas (new residential subdivisions) with wildland fuel piles spaced 25 ft apart in one series of burns and 115 ft apart in another series. The test plots used range in size from 1 to 10 city blocks (218,000 to 2,200,000 sq ft). The number of simulated houses burned was either 9, 36, 81, or 420. In all but one plot, the "streets" were arranged so that they were straight; in one plot alternate rows were offset to simulate blocked streets. The fuel weight and size-of-fuel-distribution was determined for the piles indirectly and temperatures, wind velocity, radiation and pressures were measured. The original reference[40] should be consulted for details; however, with regard to coalescence of convection columns, several results seem pertinent here. For example, it was shown that the maximum air entrainment may occur well above the base of the fire. Also, since

these tests showed that fire whirlwinds tended to develop in areas where opposing air currents or eddies occur, and since firestorms are possibly large scale vortices or groups of vortices, this factor may be important in the development of firestorms. The fires, after an initial flaming period, tended to break up into smaller fires each with a separate convection column. Above the fire, the movement of gas was found to be turbulent with both upward and downward currents. Above the turbulent zone, the convection columns merged and the flow was more organized.

Countryman[40] states that the height of flames in the fire is controlled principally by laws governing multiple jet orifices, that the temperature above the turbulent zone is much lower than in the turbulent zone, and that this rather abrupt change in temperature may have more of an effect on convective activity than previously supposed and may be responsible in part for the air-mass instability present in large fires.

APPENDIX F

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13. ABSTRACT The parameters governing the fire vulnerability of U.S. urban areas from nuclear bursts have been identified, defined, and evaluated in terms of their relative importance, interactions, and sensitivity characteristics. The results will be useful in fire-vulnerability assessment studies.

A comprehensive listing of parameters in decreasing order of importance is presented with the ranking of these parameter groups for the following seven categories of urban fire response:

Type 1 -- Fire Vulnerability is Determined Primarily by the Extent and Number of Initial Fires Caused by Thermal Radiation. (Category A. Limited Thermal Shielding, Category B. Extensive Thermal Shielding.)

Type 2 -- Fire Vulnerability is Determined Primarily by Spread or Ultimate Magnitude of Fire. (Category A. Spreading Fire of Conventional Magnitude, Category B. Conflagration, Category C. Firestorm.)

Type 3 -- Fire Vulnerability is Determined Primarily by Fires Resulting from Blast or Other Causes. (Category A. Blast-Caused Fires, Category B. Panic-or False-Alarm-Caused Fires.)

Recommendations are made for further research into significant areas where major information gaps exist.

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